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MASTER

REON

ROCKET ENGINE OPERATIONS — NUCLEAR

REPORT NO. RN-S-0058

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

COLD FLOW TEST OF REACTOR CLUSTER AND SUBSTITUTE REACTOR CLUSTER (U)

NERVA PROGRAM

CONTRACT SNP-1

APRIL 1964

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Classification cancelled (or changed to ~~~~)
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by G. C. TIC, date

ROCKET ENGINE OPERATIONS — NUCLEAR

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SPECIAL RE REVIEW FINAL DETERMINATION
Class: U
Reviewer: JRP Class. U Date 2/23/82

GROUP 1

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RN-S-0058

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ABSTRACT

This report describes a test program which was conducted to determine whether the cold-flow (with H_2 gas) thermal characteristics of an NRX-type graphite reactor core can be simulated by a metal core during the transient period of the Cold-Flow Development Test System. A substitute full-scale metal core, capable of providing thermal simulation, is described. Transient test data are compared with the results of an analog-computer model transient study for the NERVA engine. Values of experimental heat transfer coefficient and friction factor for the flow of hydrogen through an NRX-type graphite fuel element are given.

W. D. Stinnett
NERVA Technical Systems Manager
REON

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TABLE OF CONTENTS

SECTION I

OBJECTIVE

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I. OBJECTIVE

The work described in this report was conducted to determine whether the thermal characteristics of a graphite reactor core in cold-flow tests could be reasonably simulated by a metal core. If simulation could be demonstrated in small scale tests, the possibility would exist that CFDTS could be conducted with a full-scale metal core, or that the metal core could serve as an inexpensive backup for a prototype core. Such a core would provide useful cold-flow data and could be fabricated at a fraction of the price of a prototype core.

SECTION II

SUMMARY

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II. SUMMARY

Analysis of the thermal properties of various materials over a temperature range from 520-200°R indicated that aluminum, utilized in a tube bundle configuration, showed promise of being a suitable metal for a simulated core. Three test pieces (two of aluminum, and one of unfueled graphite), approximately equivalent in size to a single cluster of the reactor core, were prepared. The graphite test piece was made up of seven unfueled NRX-type graphite fuel elements. The pertinent characteristics of each test piece are given in the following tabulation:

Test Piece	Width-inches	Weight lb	Material	Number of Holes or Tubes	Hole dia. inches	Total Heat Transfer Area-inches^2	Total Flow Area-inches^2	Basic Dimensions inches
1	2.25 across flats	9.3	Unfueled Graphite	118	0.096	1850	0.856	Std. Hex. 7 pieces, 52-in. long
2	1.50 across Hex.	5.7	6061-T6 Aluminum	164	0.085	2280	0.930	0.125 OD 0.085 ID 52-in. long
3	2.50 dia.	14.4	6061-T6 Aluminum	134	0.090	1970	0.852	0.187 OD 0.090 ID 52-in. long

Test Piece No. 1 represented a cluster of the reactor core and was made up of seven hexagonal unfueled graphite elements, which were cemented together. The design of Test Piece No. 2 was based on the assumption that equivalent heat capacity over the expected temperature range would be the predominant factor in simulation of a graphite core. Test Piece No. 3 provided flow area simulation and a heat capacity about twice that of the graphite core. By testing sections of different heat capacity, it was felt that more conclusive evidence could be obtained that heat capacity is the controlling factor in cold flow simulation.

The three test pieces were individually installed in a test fixture with appropriate instrumentation, were insulated from their surroundings, and were flow tested with GH_2 which had been chilled to approximately 180°R by its passage through

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a LN_2 heat exchanger. Test conditions in terms of pressure level, H_2 temperature, and flow rate were based upon the range of parameters indicated in an analog model study of the NERVA start transient.[1]

Simulation of the graphite section by an aluminum test section would be demonstrated if the rate of heat exchange and quantity of heat removed from the test pieces by the H_2 gas (as measured by the enthalpy change of the gas) were essentially the same during the transient period.

A total of eleven tests were conducted, one a checkout test, four with graphite test piece No. 1, five with aluminum test piece No. 2, and one with aluminum test piece No. 3.

All tests were made under the following conditions:

1.	Duration of transient heat-exchange period	$\sim$10 sec
2.	H_2 gas flow rate (constant)	$\sim$0.10 lb/sec
3.	Pressure level at test-section inlet	
	At 3 sec	$\sim$150 psia
	At 10 sec	$\sim$120 psia
4.	Gas temperature at test-section inlet	
	Initial (0 - 4 sec)	$\sim$520 - 200°R
	Final (4 - 10 sec)	$\sim$200 - 180°R

The tests indicated that the thermal energy given up to the H_2 gas by aluminum test piece No. 2 was nearly the same as that exchanged with the gas by graphite test piece No. 1. The pressure drop across the two pieces was about the same. Thus, a simulated core, the design of which is based upon the tube configuration of test piece No. 2, should provide excellent thermal simulation of the graphite core. Such a core would be 54.25 in. long and 30 in. in diameter, and would be made up of about 47,000 1/8-in.-dia tubes. Of the above length, 2.25 in. represents the support blocks in the real core. The ROM cost to fabricate one such core, including aluminum support rings at each end, is estimated to be $25,000.

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[1] REON Report No. 2710, <u>Revised Test Plan for Cold Flow Development Test System</u>, Confidential, September 1963.

It was demonstrated that materials with approximately the same ratio of heat capacity to cooling area would exchange equal amounts of energy at equal rates with H_2 gas. Since the temperature gradients across the thin walls of the aluminum and graphite test pieces are extremely small in a chill-down test, the diffusivity of the two materials appears not to be a controlling factor in thermal simulation.

The heat-transfer coefficient determined from tests of both the graphite and aluminum test pieces is about half of the value calculated from the McAdams' formula. Representative values are:

$$h_g \text{ (McAdams)} = 0.0014 \text{ Btu/in.}^2 \text{sec } ^{\circ}\text{R}$$

$$h_g \text{ (Test D-111-LC-5)} = 0.00075 \text{ Btu/in.}^2 \text{ sec } ^{\circ}\text{R}$$

The friction factor for the unfueled graphite element, based upon differential pressure measurements from Tests D-111-LC-2 to 5 inclusive, lies between 0.0235 and 0.0438, with an average "f" of 0.034 at an average "R_e" of 35,000.

The test data from the graphite cluster was compared with the results of the start transient study made for the NERVA engine on the analog computer model. It was found that the time-wise variations of experimental and computed core outlet gas (chamber) temperature and graphite wall temperatures are in reasonable agreement over that portion of the transient period for which the expected inlet gas temperature to a full-scale core could be duplicated in test.

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SECTION III

CONCLUSIONS AND RECOMMENDATIONS

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III. CONCLUSIONS AND RECOMMENDATIONS

A graphite core can be thermally simulated by a bundle of aluminum tubes. The voids between tubes are not detrimental, since radial heat flow, as proven by test results, is not a significant factor in the simulation. The metal substitute core can be fabricated by conventional methods at a fraction of the price of a prototype core. It is recommended that one metal core be proposed as a backup for the prototype core to be used in the CFDTS program.

It is recommended that the installation of thermocouples on graphite test pieces be evaluated in terms of wire size and method of attachment so that these parameters may be defined with relation to their expected response in the CFDTS program. Preliminary tests in the subject program produced unexpected results.

The concept of a bundle of aluminum tubes which thermally simulates a graphite core can be a useful research tool because of the ability to measure wall temperatures at nearly any location throughout the bundle. Thus, axial and radial temperature distributions during cold flow can be determined with reasonable simulation of the results to be expected in a multi-hole graphite core.

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SECTION IV

TEST HARDWARE

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IV. TEST HARDWARE

A. MATERIAL PROPERTIES AND BASIS FOR DESIGN OF ALUMINUM TEST PIECES

The properties of interest in any thermal simulation are conductivity, specific heat, diffusivity ($K/\rho C_p$), and density. Figures 1, 2, and 3 show the variation in these properties for aluminum and graphite over a 200°-$500^{\circ}R$ temperature range. The source of these data is noted on the particular figures. It is to be noted that the conductivities of aluminum and graphite are about equal (80 Btu/ft-hr-$^{\circ}R$) over a 250 - $500^{\circ}R$ temperature range. The specific heat of aluminum is about twice that of graphite when averaged over a 250 - $500^{\circ}R$ temperature range (0.187 Btu/lb $^{\circ}R$ for aluminum and 0.115 Btu/lb $^{\circ}R$ for graphite). The diffusivity of graphite is higher than that of the aluminum, primarily because of the difference in specific heat. Density of the two materials is about 0.070 lb/in^3 for graphite and 0.098 lb/in^3 for aluminum.

As indicated previously, the basis for the design of test piece No. 2, was the matching of the heat capacity of the graphite and aluminum parts over the 250 - $500^{\circ}R$ temperature range. The surface area exposed to the coolant should also be as nearly equal as possible. Utilizing these criteria, and based upon the fact that the graphite cluster weighed 9.3 lb, the desired weight of aluminum test piece No. 2 was calculated to be 5.7 lb. With the weight of the tube bundle established, the individual tube size was chosen from commercially available stock and the number of tubes was based on the weight requirement.

The design of test piece No. 3 provided a flow area equal to that of the graphite test piece. Again, a commercially available tube size was chosen. Utilizing 3/16-in.-OD tubes, 134 tubes were required to match the flow area. This number of tubes gave a test piece the heat capacity of which was more than two times that of the graphite section.

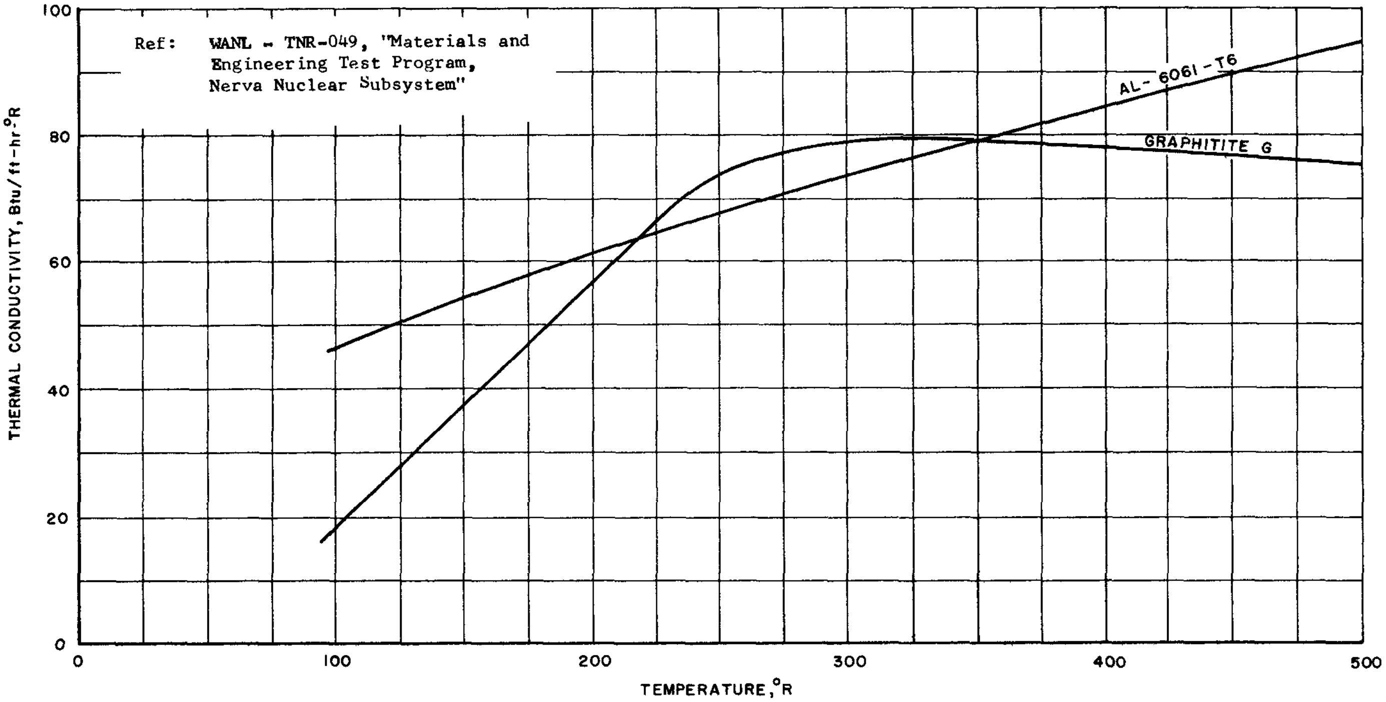

Figure 1

Aluminum and Graphite Conductivity
As a Function of Temperature

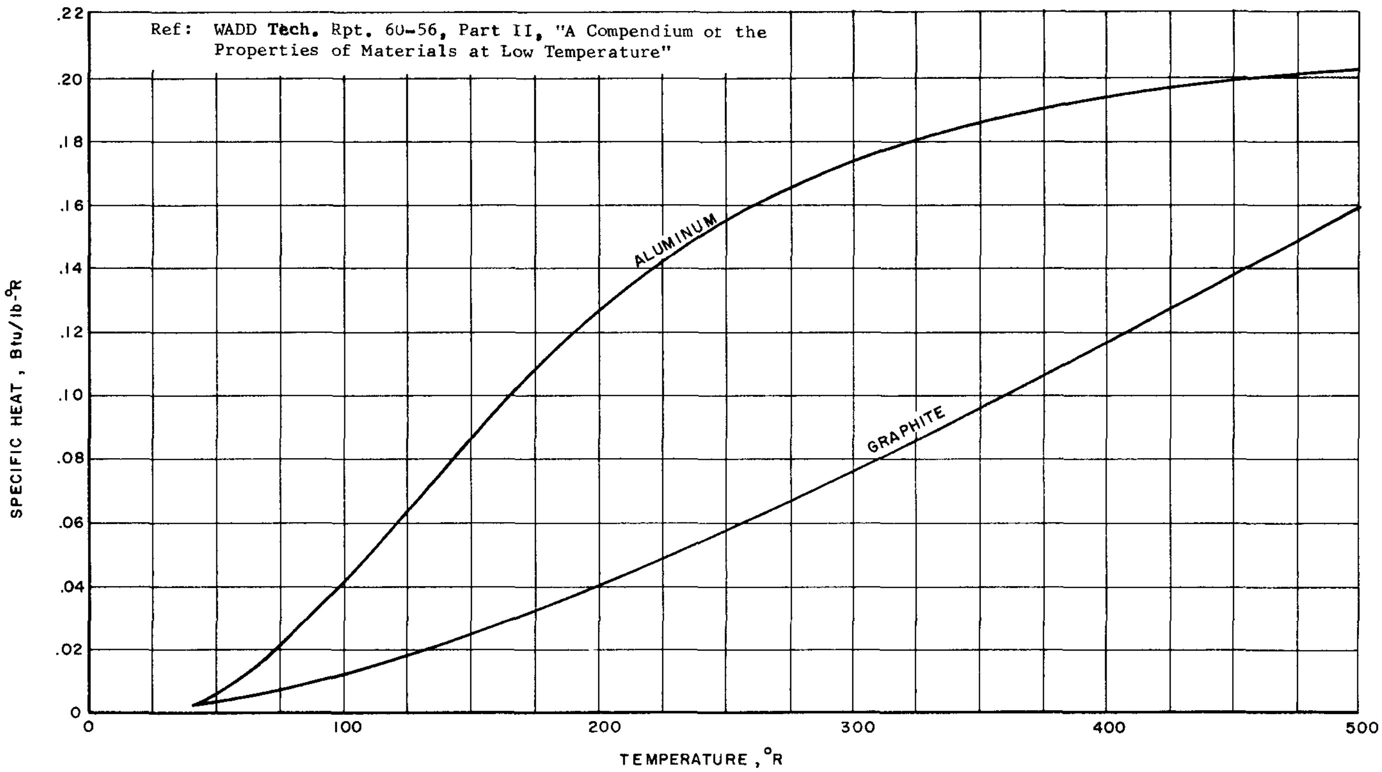

Figure 2

Aluminum and Graphite Specific Heat
As a Function of Temperature

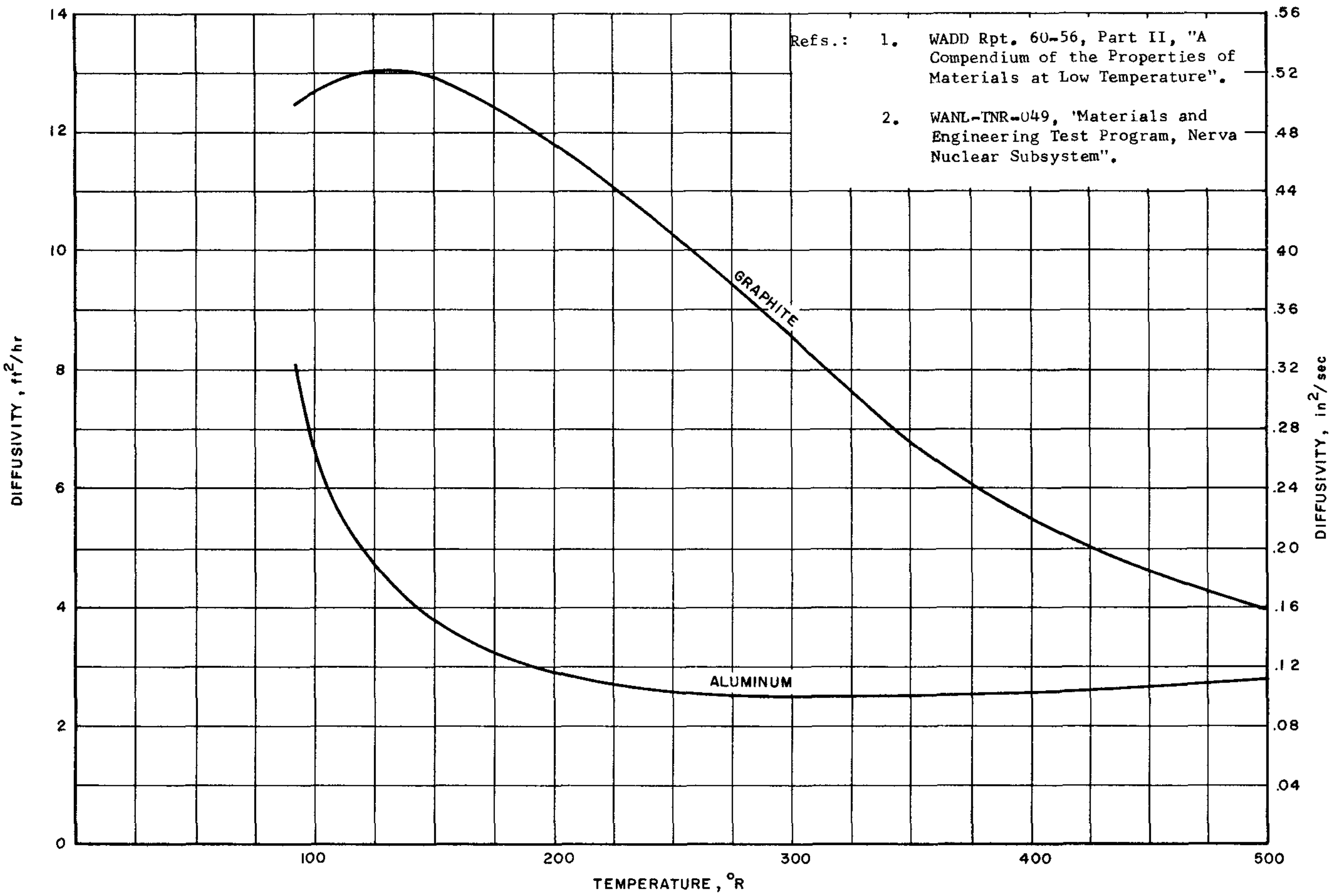

Figure 3

Aluminum and Graphite Diffusivity
As a Function of Temperature

B. TEST PIECE DESCRIPTION

1. Graphite

The graphite test section, shown in Figure 4, consisted of seven 3/4-in. hexagon unfueled graphite elements, each 52 inches long, cemented together at each end with pliobond cement. The cement not only provided an integral unit for test but also prevented any flow of H_2 gas around the outside of the hexagon elements. Fourteen of the nineteen holes in the center hexagon section were plugged. The five holes represented the cooling area surrounding the tie-rod in a real fuel cluster. Thermocouples were bonded to the outer wall of the graphite by means of Epoxy No. 921 cement.

2. Aluminum

The two aluminum test sections(one of which is shown in Figure 5) comprised a bundle of tubes, the dimensions of which have been previously indicated. Each tube bundle was made into an integral unit by welding closed the voids between the tubes at one end. The tubes were held together at the opposite end by means of suitable clamps.

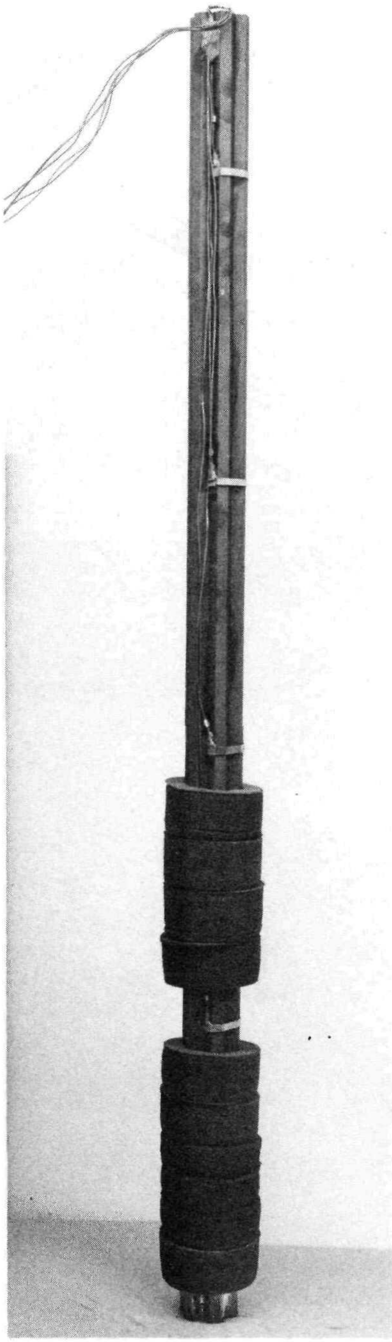

Figure 4

Graphite Test Piece

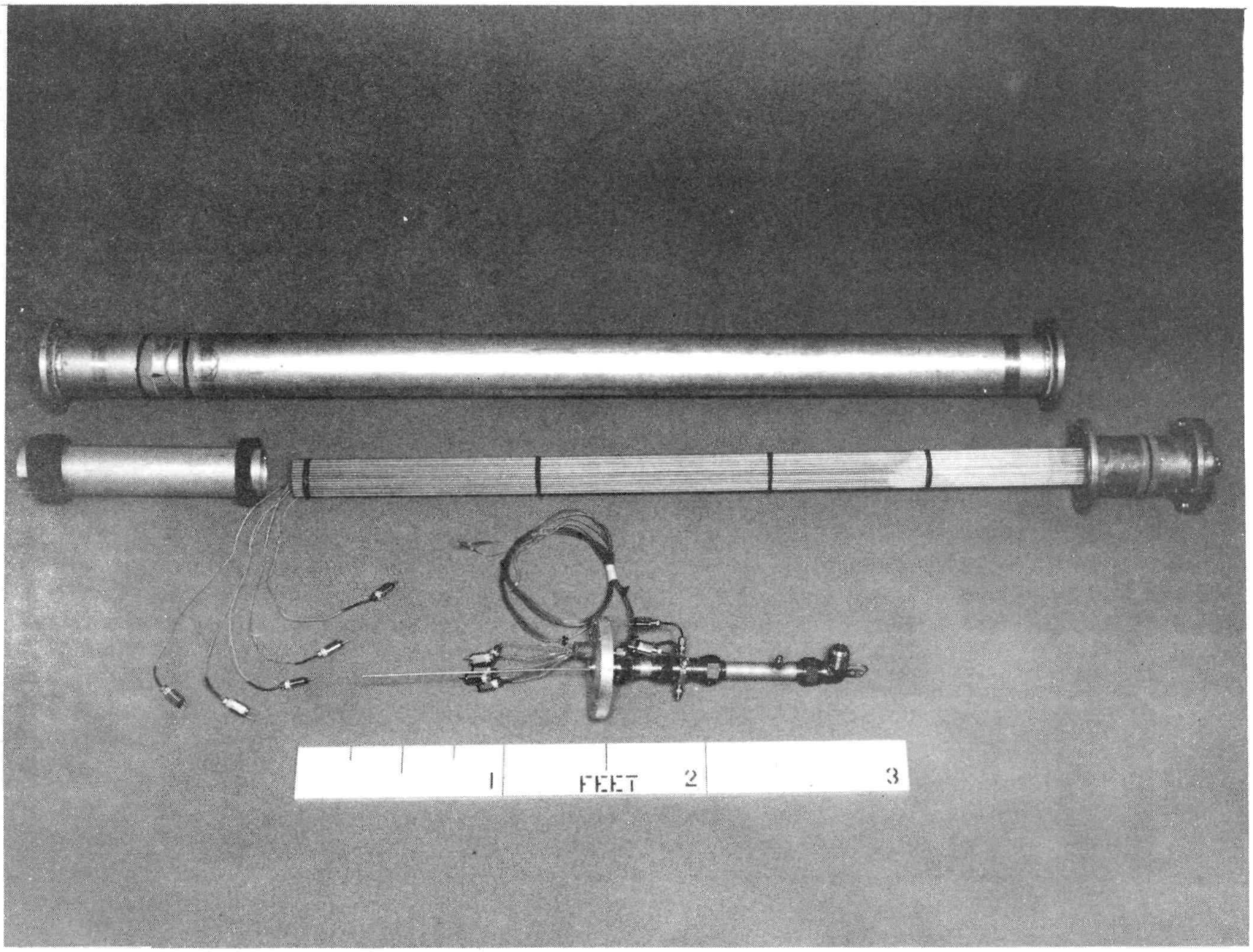

Figure 5

Aluminum Test Piece No. 2

C. TEST FIXTURE

The design of the test fixture is illustrated in Figure 6. This design was developed to secure the test piece (whether graphite or aluminum tube bundle) within a two-piece aluminum housing, and at the same time to provide a positive seal at one end so that all gas would be channeled through the flow channels in the test piece.

Cerrobend, cast in the space between the housing and the test specimen, connected the specimen to the housing, and provided the seal at the aft end of the test fixture. Figure 7 is a photograph of the Cerrobend joint. Photographs of the test fixture are given in Figures 5 and 8. Sufficient space was allowed between the exterior of the test piece and the housing wall so that insulation (in the form of polyurethane wafers) could be mounted around the test piece and cover its full length. Although a small amount of H_2 gas was free to flow into the annular space occupied by the polyurethane, it would become quiescent and would have negligible effect upon the change in temperature experienced by the test section. The polyurethane material also provided a soft lateral support for the test section.

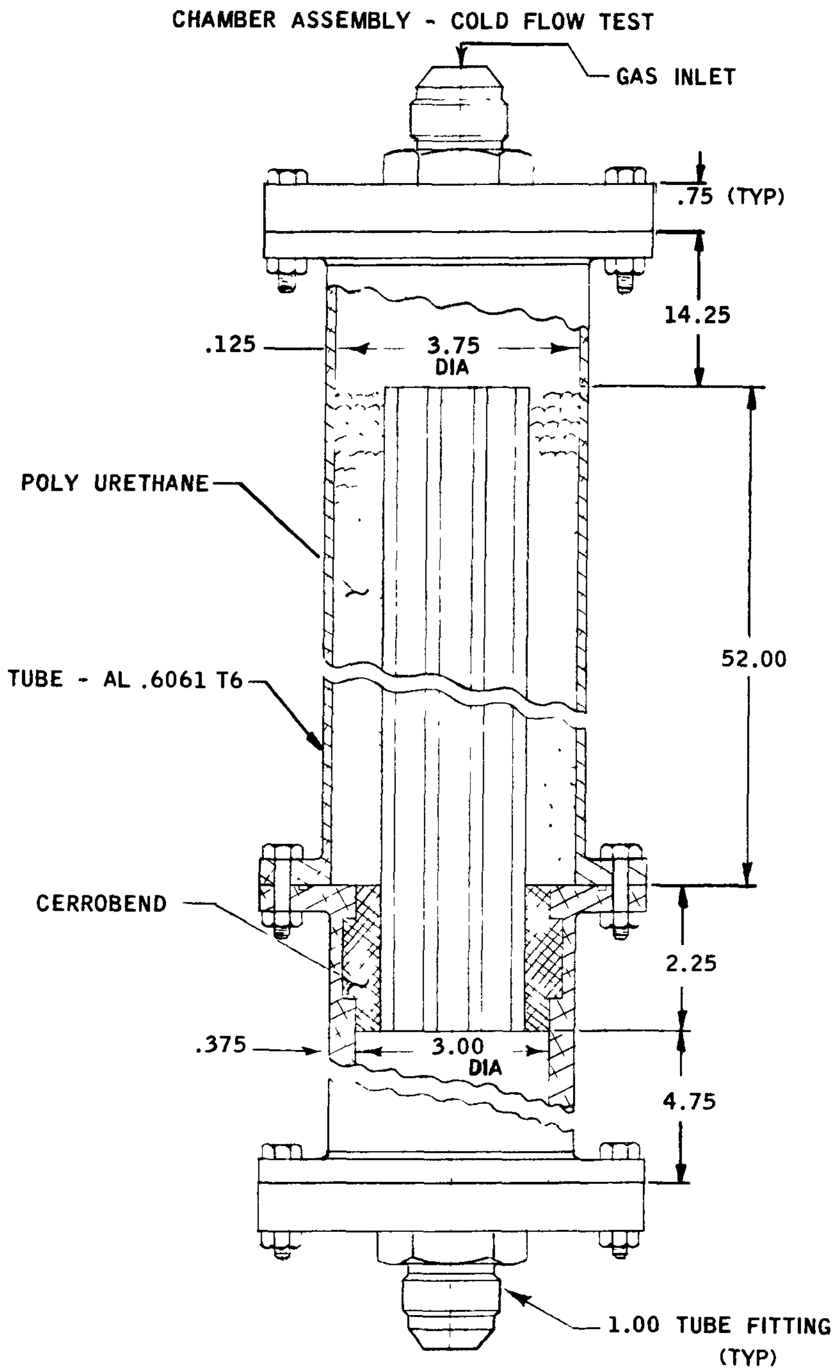

Figure 6

Test Fixture Assembly

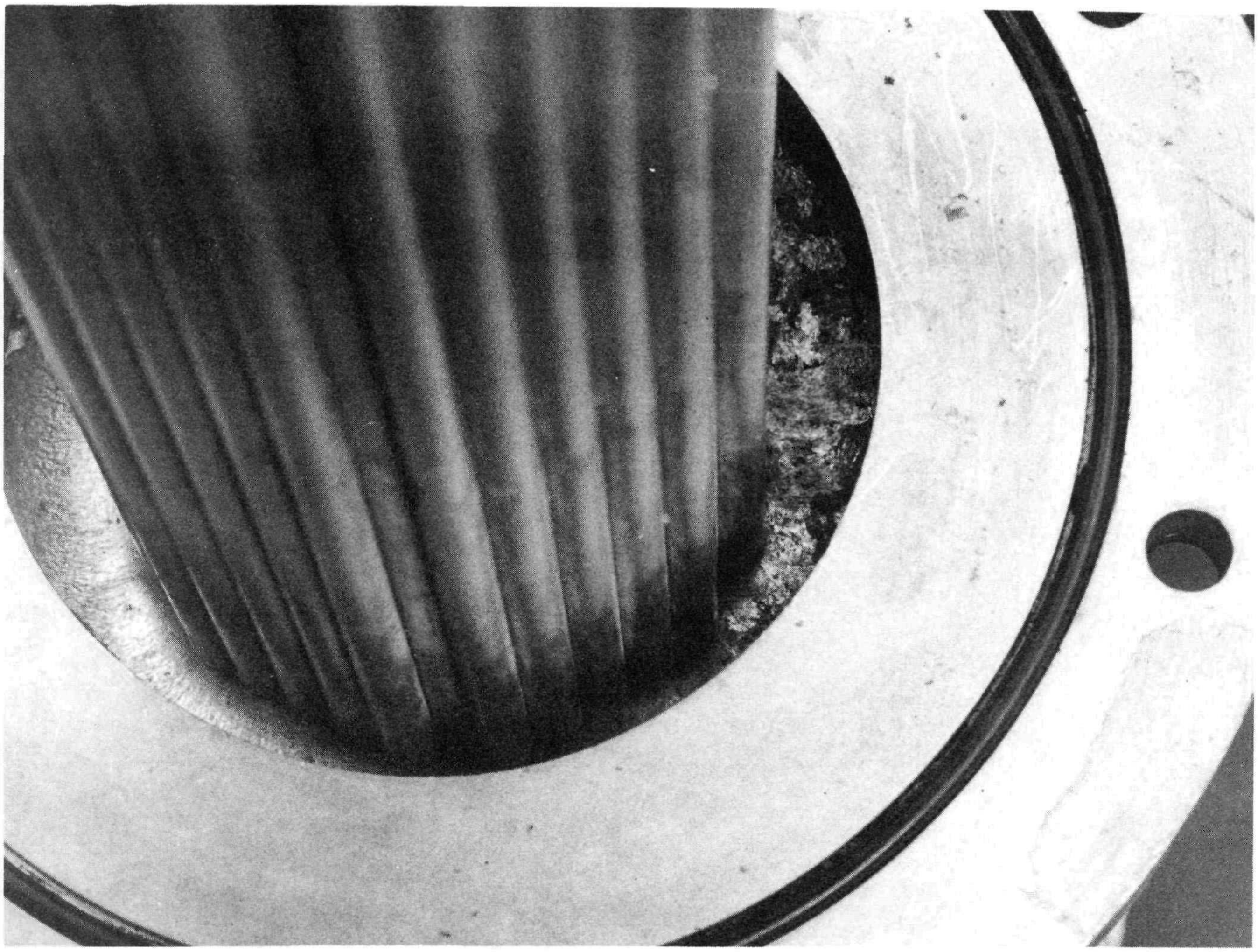

Figure 7

Cerrobend Joint

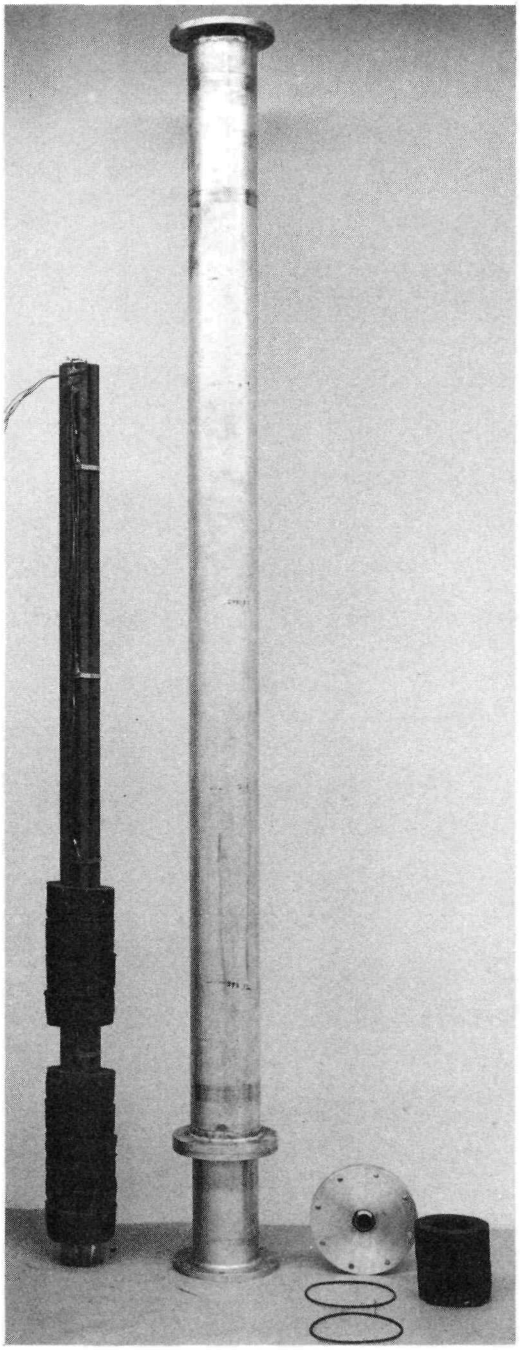

Figure 8

Test Fixture Assembly

D. THERMAL ISOLATION OF TEST PIECE

To meet the objectives of the experiment, it was necessary to determine and compare the amount of heat removed from the several test pieces by the H_2 gas. Appreciable heat pickup by the gas or the test piece from other materials would invalidate the experiment, unless it could be demonstrated that such heat pickup took place after the transient period of interest, or was a constant amount from test to test.

The change in enthalpy of the H_2 gas as it passed through the test section, was recorded by bare-wire chromel-alumel located within several inches of the inlet and outlet of the test section. Although some heat could flow from the aluminum housing into the H_2 gas, in the space between the ends of the test section and the thermocouple, the surface area in contact with the gas was believed to be so small as to have negligible effect on the temperature change of the gas as it passed through the test section.

As previously mentioned, the test pieces were thermally isolated from the aluminum housing by approximately 3/4-in.-thick polyurethane foam wafers. It was recognized that heat from the aluminum housing could be transmitted to the test piece through the Cerrobend. Again, it was felt that the amount of heat flowing by this path would be small during the significant part of the chill-down transient. It is to be noted that the aluminum housing assembly (containing the test piece) was completely covered by a bonnet and subjected to an external vacuum of about 1000 microns. Thus, the only significant heat which could be transmitted to either the gas or the test piece was the sensible heat contained in the housing and associated parts.

As the test series progressed, it was apparent that some heat was being added to the H_2 gas by the aluminum wall of the test fixture. Although the major part of this heat exchange took place after the initial transient period of about 6 seconds (as evidenced by TW-6, which recorded the fixture wall temperature at the inlet to the test section), it was felt desirable to minimize the heat transfer to the gas to improve the accuracy of the experiment. Accordingly, insulation was added at the inlet and outlet sections of the basic fixture to provide as much insulation as possible between the aluminum wall and the gas. The tabulation below indicates the various types of insulation which were added to the inlet and outlet plenum and the test numbers applicable to each type of insulation.

Test No.	Test Piece Insulation	Inlet & Outlet Plenum Insulation
2 - 7	Polyurethane	None
8 - 9	Polyurethane	Cardboard - 1/8 in. thick
10 - 11	Polyurethane	Inlet plenum - polyurethane wafers retained by a thin wall aluminum tube spot welded to inlet cover plate. Outlet plenum - Cork

SECTION V

TEST INSTALLATION

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V. TEST INSTALLATION

A. COLD FLOW SYSTEM

Figure 9 is a schematic diagram of the Cold Flow System. Figure 10 is a photograph of the test installation. The Cold-Flow System comprised, in order, a bank of high-pressure gaseous-hydrogen bottles, a pressure regulator, a sonic flow control orifice, a metering orifice, an LN_2 heat exchanger, a flow circuit through the test section paralleled by a by-pass flow circuit, a discharge line containing a back-pressure orifice, and a vent stack for discharging the H_2 gas to atmosphere. Miscellaneous purge, vent, and vacuum connections were provided in the piping upstream of the test section. Special fittings were provided in the lines for attachment of pressure and temperature transducers.

The system was designed to deliver H_2 gas (chilled to near-LN_2 temperature) at a constant flow rate of about 0.10 lb/sec to the test piece at an initial pressure of about 150 psia. With a constant-size back-pressure orifice and a variable temperature gas flowing out of the test section, some change in the pressure level of the test section was anticipated during a test.

The inlet line to the test section is a piece of 1-in.-OD x 0.049-in.-thick aluminum tubing about 10 ft long. This tubing, which is contained within the evacuated space surrounding the test fixture, weighs approximately 2 lbs.

The mass of material in this line had a significant effect upon the temperature history of the gas delivered to the test piece. The temperature of the gas coming out of the heat exchanger was about 160°R. This gas, as it flowed through the room-temperature inlet line, picked up heat and was warmed briefly to about 500°R. With the chilling of the line, the temperature of the H_2 gas entering the test section would drop rapidly and approach an equilibrium temperature of about 180 - 200°R within 5 seconds of initiation of flow into the test section. As will be indicated in Section VII,B, the variable inlet gas temperature obtained in the tests duplicates rather closely the expected variation in gas temperature as it enters the core from the shield.

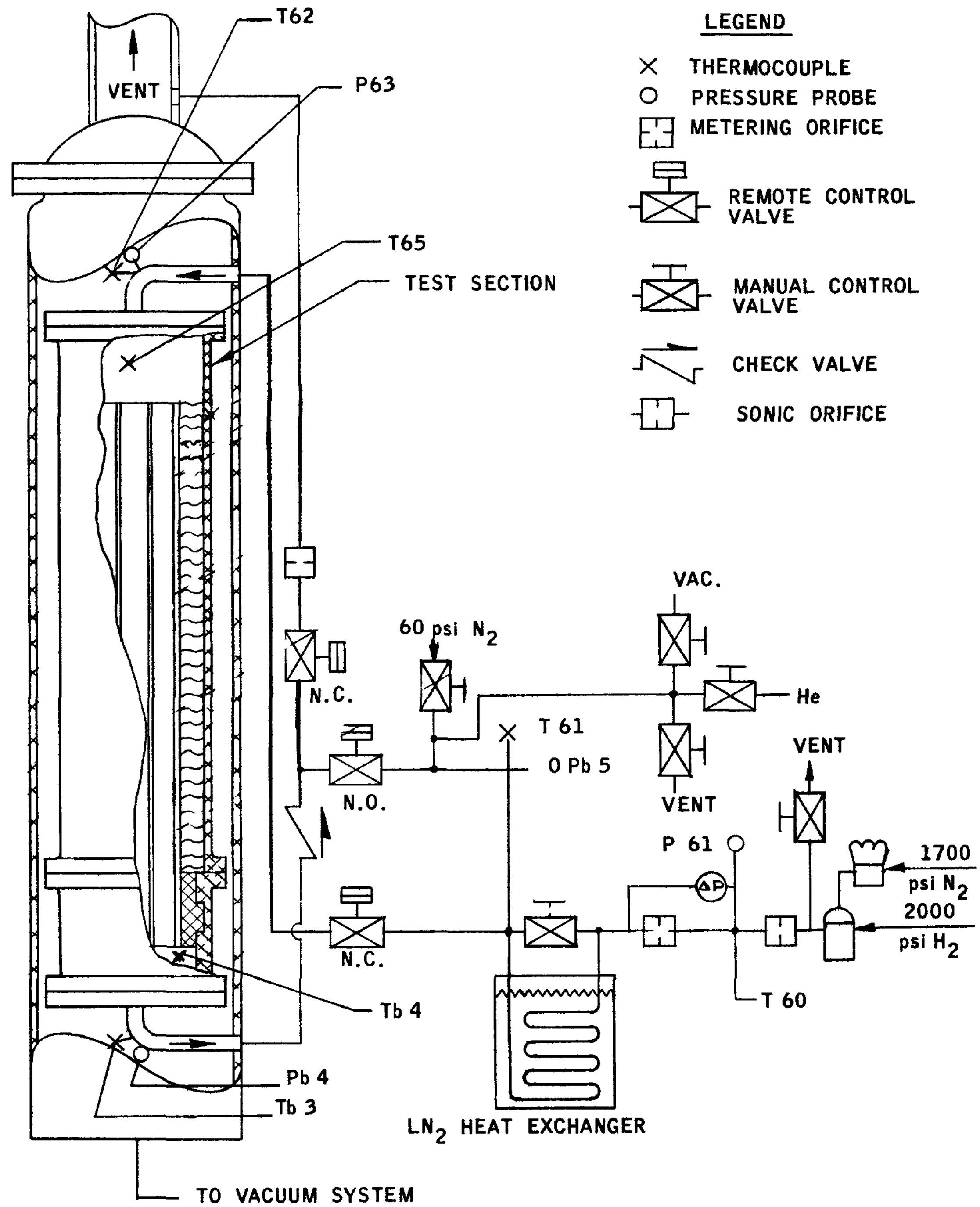

Figure 9

Test System Schematic

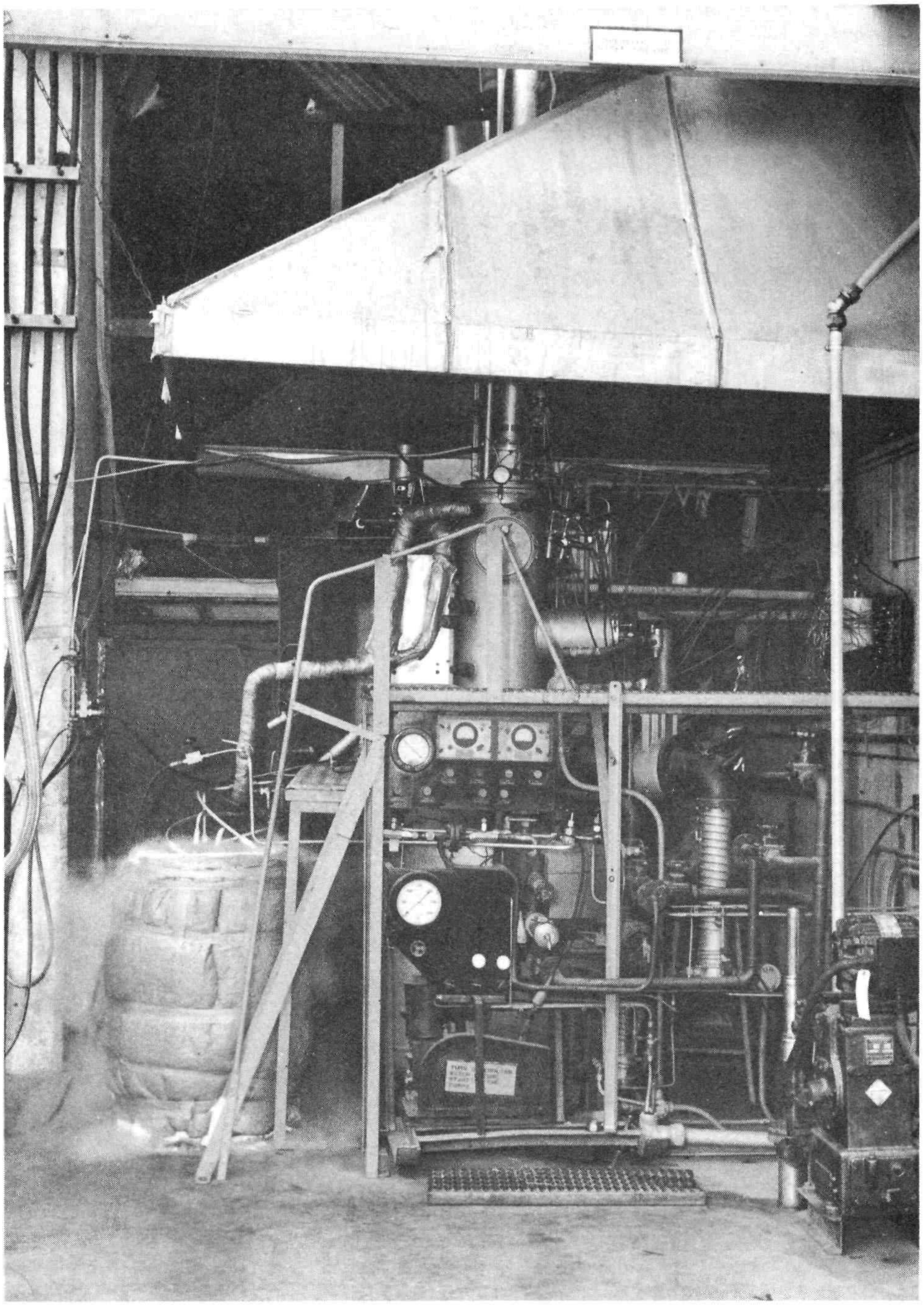

Figure 10

Test Installation

B. INSTRUMENTATION IDENTIFICATION AND LOCATION

H_2 flow was determined from the differential pressure measured across a sharp-edged orifice. The orifice was calibrated with N_2 gas at room temperature and the readings were corrected for the density change to H_2 gas. A Wianco pressure transducer measured the differential pressure.

All pressures in the system were measured by Wianco pressure transducers, the locations of which are shown in Figure 9.

The differential pressure across the test section was measured by a Pace gage (utilized in Tests 5-11, inclusive).

Gas temperatures were measured by No. 22 bare wire I.C. and C.A. junctions contained in a 1/8-in.-dia. stainless-steel sheath. Identification and location of the gas temperature measurements are given in Figure 11.

Wall temperatures were measured by I.C. thermocouples. Wire size and method of attachment to the test section are indicated in this tabulation:

Applicable Tests	Test Section Material	Bonding Agent	Wire Size
2 - 5	Graphite	Epon 921	No. 16
6 - 8	Aluminum	Epon 921	No. 16
9 - 11	Aluminum	Plastic Tape	No. 24

Identification and location of the wall temperature measurements are given in Figure 11. Certain changes in identification and location of the thermocouples took place in the latter part of the test series. This information is presented in the figure.

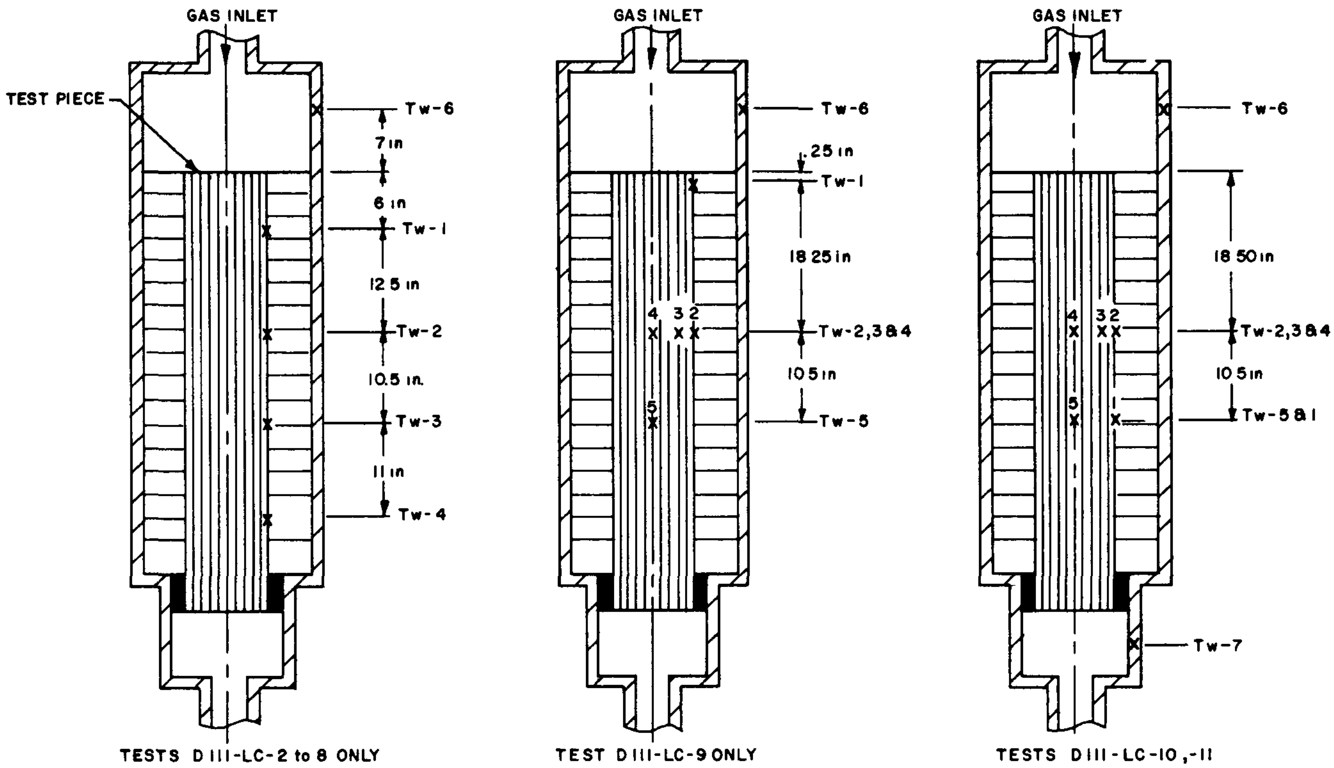

Figure 11

Thermocouple Locations

C. RECORDERS

Leeds and Northrup, and Brown self-balancing potentiometers were used to record all pressures and temperatures in Tests D-111-LC-2 thru 5. Starting with Test D-111-LC-6, inlet and outlet gas temperatures were switched to an oscillograph to provide better timing correlation between measurements. Also, the bypass valve trace was added to the oscillograph trace to indicate precisely when H_2 gas was introduced into the test section.

SECTION VI

TEST PROGRAM

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VI. TEST PROGRAM

A. BASIS FOR COLD FLOW REQUIREMENTS

REON Report No. 2710 presents the range of pressures, flow rates, and temperatures expected during CFDTS startup tests. This start transient data was obtained with the power-range analog simulation of the AJ 30-5 hot-bleed cycle engine. Figure 12 is a reproduction of certain of these data, and gives the timewise variation of flow, pressure, and temperature when the TPCV angle is 60° open and the tank pressure is 25 psia. These relationships provided the basis for establishing the conditions under which the single cluster should be flow tested in the subject program.

As noted in Figure 12, the flow rate through the full-scale core (comprised of about 280 clusters) is expected to be essentially constant during the first six seconds of the startup period and equal to about 30 lb/sec. Thereafter, flow rate through the core would decrease at a certain rate. Based upon this total flow rate, the flow rate through a single cluster was established as a constant value of about 0.10 lb/sec, to duplicate initial flow conditions in the full-scale core. Constant flow was to be obtained by installing a sonic orifice in the gas circuit upstream of the LN_2 heat exchanger, where regulated pressure and essentially constant temperature (520°R) conditions would prevail.

In the full-scale core, chamber pressure and the inlet pressure to the core are expected to rise to a value of about 100 psia, remain constant at this value for a few seconds, and then slowly decay. This pressure level was approximated in the subject system by the proper choice of a back pressure orifice downstream of the test section. With a variable temperature gas flowing through a constant size orifice, a reduction in pressure would be expected during a transient period.

In the full-scale core, the initial temperature of the gas entering the core is of the order of 450°R. In a period of about 5 seconds the temperature of the gas is expected to chill to approximately 100°R. This timewise variation in inlet gas temperature was simulated over a portion of the temperature range (450-180°R) by the heat exchange between the 160°R gas and the ambient temperature inlet line. (See Section V,A.)

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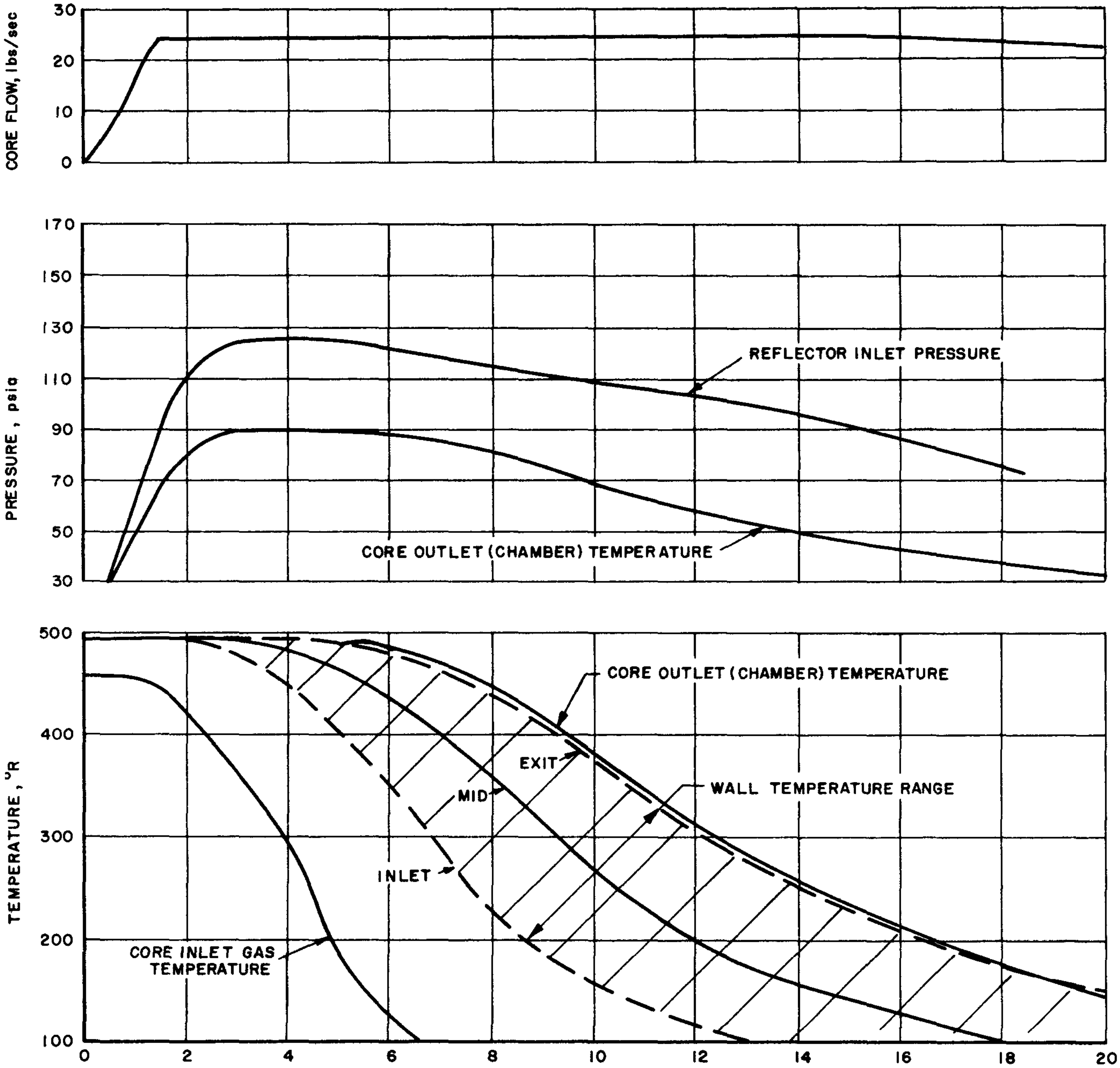

Figure 12

Start-Transient Data
Flow, Pressure, and Temperature
As a Function of Time

B. TEST PROCEDURES

The test procedure may be quoted:

1. Alternately purge with He and evacuate all lines and the test section. Pressurize and maintain pressure in system at 20 psi with He gas.

2. Fill heat exchanger with LN_2.

3. Activate the gaseous hydrogen supply and initiate flow through the heat exchanger and bypass loop, by opening the vent valve. Adjust mass flow rate to the desired value. When the temperature of the gas leaving the heat exchanger is at the desired value (recorded visually), simultaneously close the by-pass valve and open the test section valve.

4. Flow H_2 gas through the test section and record data until the inlet and outlet temperatures indicate achievement of equilibrium conditions.

5. On shut-down, purge the inlet line and test section with room temperature N_2 gas until the temperature of all materials has returned to ambient conditions.

6. If no more tests are to be conducted, the H_2 gas contained in the coils of the heat exchanger shall be allowed to remain until all LN_2 has boiled off. At this time the H_2 gas should be purged from the circuit with N_2 gas. (This procedure insures that purge nitrogen will not be condensed in the coils and remain there as a contaminant.)

[redacted]

C. AUTO-IGNITION OF H_2-AIR MIXTURE

An explosion occurred in the aluminum tubing of the heat exchanger after flowing H_2 gas through the by-pass circuit for about 30 seconds prior to Test D-111-LC-6. The system had been operated four or five times prior to this occurrence without difficulty. No change in purge or operating procedures had occurred between tests. The purge procedure had been to flow nitrogen gas through the coils for a certain period of time and then hold nitrogen gas in the coils under essentially atmospheric pressure, while filling the drums of the heat exchanger with LN_2. The initial flow of hydrogen gas to enter the coils would then drive the N_2 gas out the vent stack.

It is postulated that chilling of the highly conductive aluminum tubing by the first bit of LN_2 in the 50 gallon drums reduced the temperature of the N_2 gas in the coils to the point that the pressure of the gas became sub-atmospheric. Under this condition, if there were any leaks in the system (either tube fitting or weld joint) air could be aspirated into the tubing and would liquefy when the temperature reaches about $230^{\circ}R$. It is assumed that several cycles of warming and chilling of the coils might have developed leaks in the system; and that finally, sufficient liquid air accumulated in the coils to react explosively with the hydrogen as it flowed through the coils.

Following repair of the heat exchanger, the purge procedure was changed to an alternate evacuation and helium purge of the circuit. No explosion took place in six additional tests, when using the revised purging procedure.

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D. TEST RESULTS

1. Graphite Test Piece - No. 1

The test program was initiated with tests of the graphite test piece. Test D-111-LC-1 was a preliminary test which indicated that the number of coils in the LN_2 heat exchanger would have to be increased by an order of magnitude to provide the degree of chilling desired for the H_2 gas. With 400 ft of 1/2-in.-dia. aluminum tubing installed, chilling of the H_2 gas to $160^{\circ}R$ was accomplished.

Tests D-111-LC-2 to 5 inclusive were accomplished under essentially the same set of conditions. The data from Test 3, shown in Figures 13, 14, and 15, are typical of the results obtained in these four tests.

Figure 13 shows that the inlet gas (Tb-2 & Tb-5) temperature reduces from ambient to $200^{\circ}R$ in about 8 seconds. Outlet gas temperature (Tb-3) lags the inlet temperature by about 4 seconds and levels out at about $240^{\circ}R$ after 15 seconds of flow through the test piece.

Figure 14 shows the graphite wall temperature (Tw-2, Tw-3 and Tw-4) reducing from ambient to $290^{\circ}R$ in about 8 seconds. Thereafter, the graphite chills at a much reduced rate and reaches $230^{\circ}R$ after 15 seconds of H_2 flow.

A comparison of the temperatures plotted in Figures 13 and 14 indicates that the average temperature of the graphite wall is nearly equal to the temperature of the gas flowing out of the test section at any particular time in the transient period.

Figure 15 shows the timewise variation in inlet pressure (Pb-3) and outlet pressure (Pb-4) for the test section. The fall-off in pressure as the test progresses was to be expected in a system having a fixed-size back-pressure orifice.

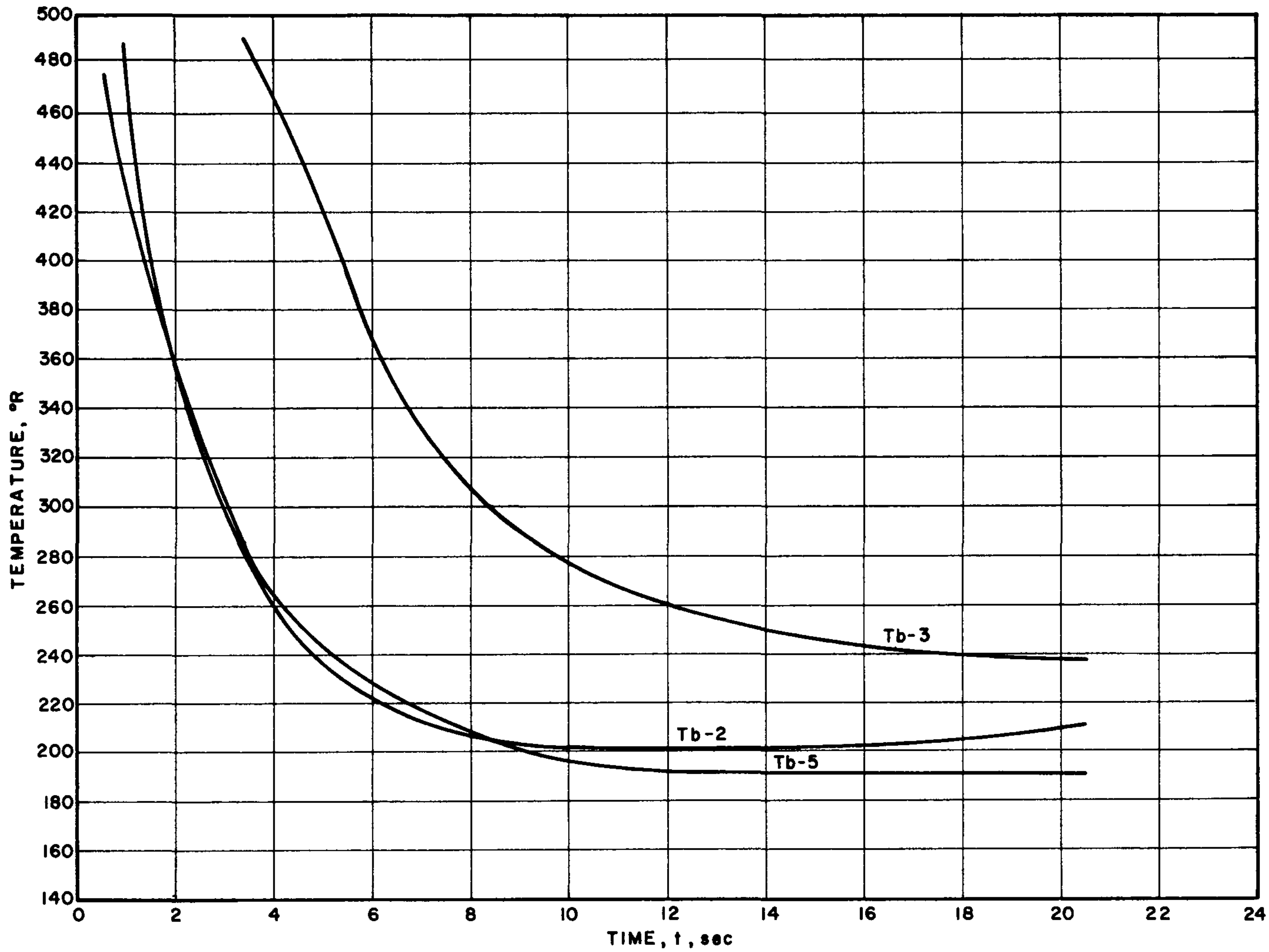

Figure 13

Test Parameters
Inlet and Outlet Gas Temperature
Test D-111-LC-3

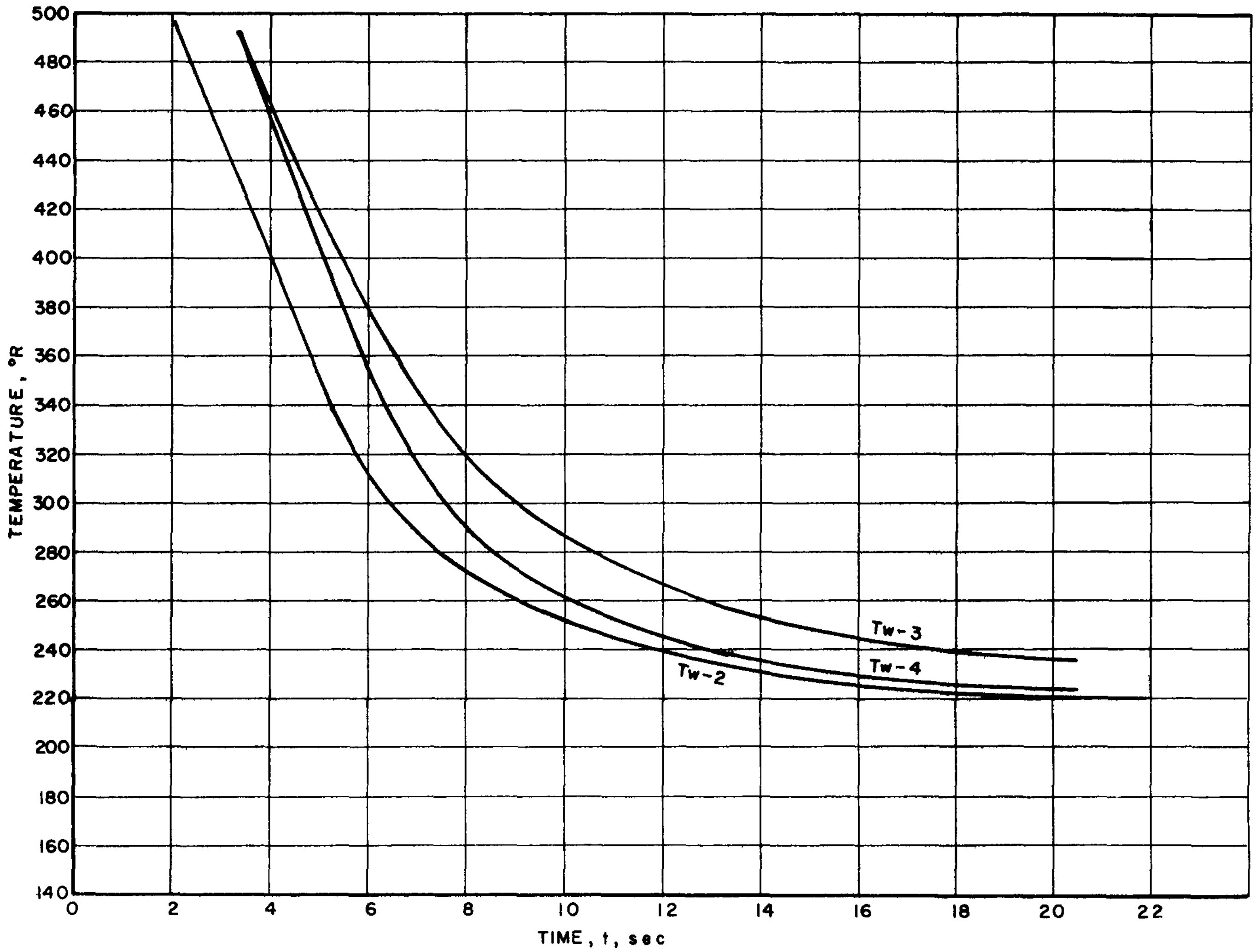

Figure 14

Test Parameters — Wall Temperatures
Test D-111-LC-3

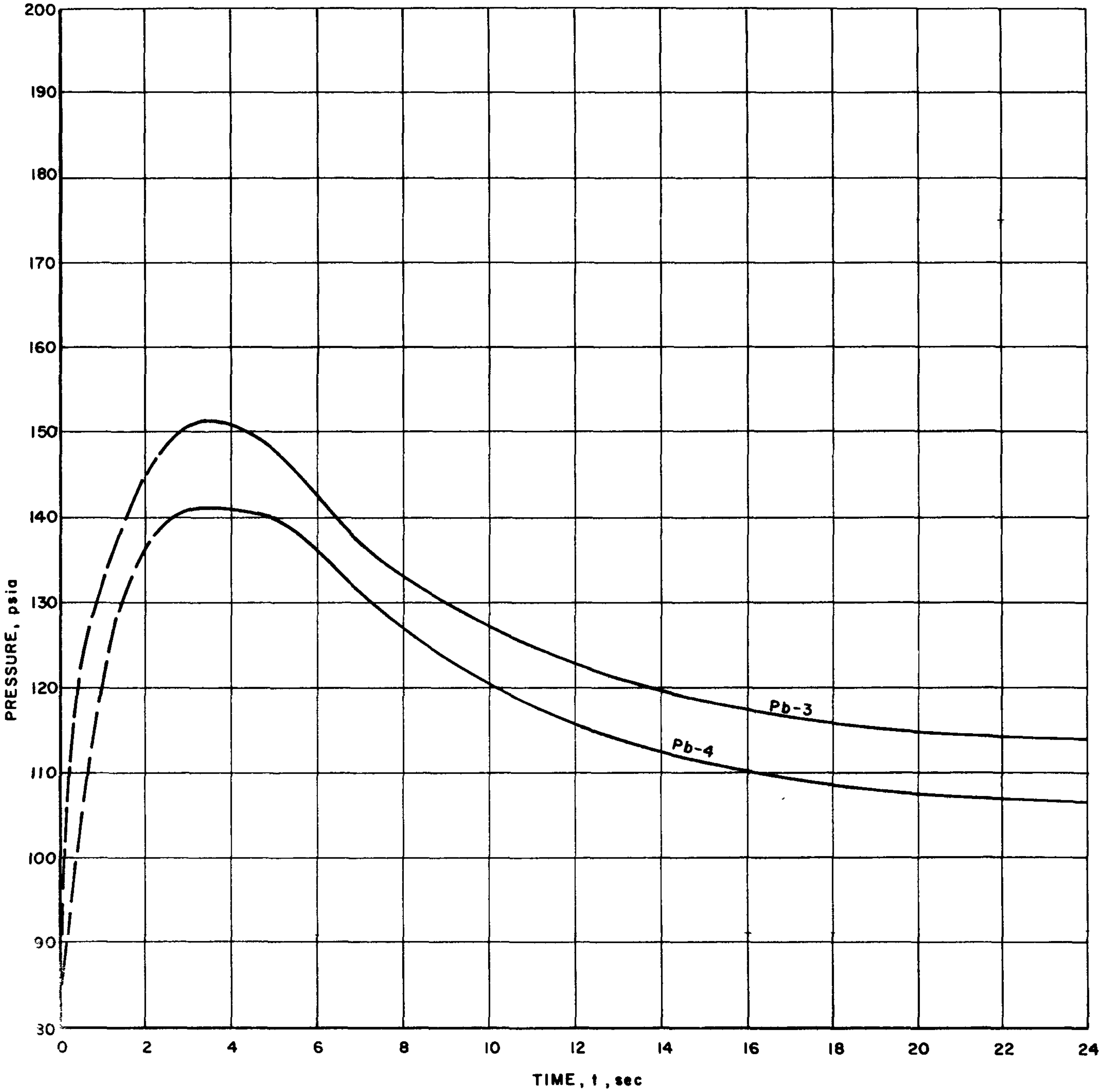

Figure 15

Test Parameters
Inlet and Outlet Pressure
Test D-111-LC-3

[redacted]

2. Aluminum Test Piece - No. 2

Aluminum test piece No. 2 was installed in the test fixture in exactly the same manner as the graphite test piece.

a. Tests D-111-LC-6 to 8

Tests D-111-LC-6 to 8 inclusive were performed under conditions which simulated those for the graphite test section. The data from these three tests indicated that the timewise relationship between inlet and outlet gas temperatures across the aluminum test section was nearly identical to that obtained with the graphite test piece. This indicates that the heat exchange between the graphite and aluminum and the H_2 gas proceeds at about the same rate, and that the thermal characteristics of the aluminum test piece, in fact, do simulate those of the graphite test piece. The record of wall temperatures for the aluminum piece, however, showed that it chilled at about half the rate of the graphite piece, which is inconsistent with the heat picked up by the H_2 gas (as represented by the inlet and outlet gas temperature measurements). Therefore, it was felt that the aluminum wall temperature measurements obtained in Tests 6 to 8 were in error, and did not present a true picture of the temperature history of the tube bundle as a whole.

It was theorized that each tube in the bundle might not have received its proportionate share of H_2 gas flow as a result of the particular entry conditions to the test section. If this were the case, wall temperature measurements taken from the walls of the outer tubes might give a fictitious temperature history for the bundle as a whole. Since very little radial heat transfer would take place from tube to tube, the thermal averaging which would take place in a graphite section would not occur to the same degree in the aluminum section.

To check this theory, the thermocouples were remounted and placed on certain of the central tubes in the bundle (as well as on the outside tubes) to provide an indication of any variation in flow or chilling of the individual tubes. Figure 11 presents the identification and location of the revised thermocouple mountings.

[redacted]

b. Test D-111-LC-9

Test D-111-LC-9 was conducted under conditions which were identical to those in Tests 6 thru 8. The wall temperature measurements in this test indicated a chill rate about twice that obtained for the aluminum section in previous tests and about the same as that obtained with the graphite test section. However, the measurements indicated little variation in the chill rate of the individual tubes, thus dispelling the theory that the chill rate of the central tubes might be more rapid than that of the outer tubes.

An examination of the outlet of the tube bundle after Test-9 indicated that several of the individual tubes in the center of the bundle had broken away from the weld which was used to join all tubes and prevent flow between them. The possibility existed, therefore, that a small amount of H_2 gas flowed in the space between tubes and chilled the thermocouple beads more rapidly than would have been the case with flow through the tube passages only. While this fact might have accounted for the difference in chill rate experienced in Test 9 (as compared with Tests 6 - 8), it was believed that a more significant difference in the two test series was the response of the thermocouples.

As indicated in Section V,B, the thermocouple used in Test-9 was No. 24 wire which was attached to the tube with plastic tape. In Tests 6 to 8, the thermocouple was No. 16 wire attached to the tubes with epoxy resin.

To determine whether thermocouple response influenced the results of Tests D-111-LC-2 - 9 inclusive and to establish the proper thermocouple installation (bonding agent and wire size) for Test-10, a small-scale investigation was performed to determine the relative response rates of various wire size thermocouples when subjected to rapid chill. The details of this program (which was conducted with thermocouple wires attached to both aluminum and graphite test pieces) are presented in Section VI,E.

For the aluminum test piece, it was found that the No. 16 wire Epon-bonded thermocouple used in Tests 6 to 8 had about half the response rate of the No. 24 wire plastic tape-bonded thermocouple used in Test 9. Thus, it is apparent that the larger thermocouple wire did not give a true indication of the chill of the aluminum tubes in Tests 6 to 8, and that the finer No. 24 wire (used in Test 9) more closely represented the chill rate of the aluminum.

The aluminum chill rate, represented by the No. 24 wire thermocouple in Test-9, is further substantiated by the temperature change of the hydrogen gas as it enters and leaves the test section. The energy exchange between the test piece and the gas must occur at the same time and same rate; No. 24 wire thermocouple correctly indicates the rate and time at which energy is removed from the aluminum test piece.

As previously indicated, the weld material which jointed the tubes of aluminum test piece No. 2 had failed in several places. Rather than reweld the section, repairs were accomplished by cementing the individual tubes together for a lineal distance of about 2 inches from the end of the section with Epon No. 921 resin and B-1 catalyst. This technique provided a leak-tight section and was more practical than welding for this particular tube size. No. 24 wire thermocouples were mounted with plastic tape on the individual tubes.

c. Test D-111-LC-10

Test D-111-LC-10 was performed under conditions duplicating those of Test-9. Figure 16 presents the timewise variation of pressure at the inlet and outlet of the test section. Figure 17 presents the timewise variation in wall temperatures at various positions across the tube bundle. Tw-1, -3, and -4 were recorded on an oscillograph, and Tw-2 and -5 were recorded on L & N recorders. Figure 18 shows the timewise variation of gas temperature at the inlet and outlet of the test section. Tb-4 and -5 were recorded on an oscillograph, and Tb-2 and -3 were recorded on L & N recorders.

Referring to the thermocouple locations of Figure 11 and the wall temperatures illustrated in Figure 17, it may be seen that the outer tubes of the bundle (Tw-1 and -2) thermally lag the central tubes (Tw-3, -4, and -5), which indicates that flow is not uniformly distributed between the 164 tubes and that the outer row of tubes undoubtedly is slightly starved of H_2, as compared with the remainder of the tubes in the bundle.

The thermal lag in an axial direction is indicated by comparing temperature Tw-4 and Tw-5 and temperature Tw-2 with Tw-1. This is further illustrated by the cross plot presented in Figures 19A and 19B which show an approximate axial temperature profile along the tube bundle and the change in this profile with time. Tw-4 and Tw-5 provide the timewise variation in wall temperature of a short portion of a central tube in the bundle. Tb-4 and Tb-5 provide the timewise variation in inlet and outlet gas temperature to this tube. The axial profile constructed from these gas and wall temperature measurements is not strictly correct, but the data do provide a qualitative picture of the heat exchange between the gas and the tube bundle.

The change in the heat-exchange pattern over the length of the tube bundle as a function of time is illustrated by the data tabulated below, in which the cooling rate of each of three sections of the tube bundle is calculated at one second intervals. The equivalence of the heat added to the gas with the heat extracted from the tube bundle may be noted in the tabulation.

	Incremental		Cumulative		Q/A (Btu/in.^{2}-sec)		
Time Interval Secs	Btu's Removed From Material	Btu's Added To Gas	Btu's From Material	Btu's To Gas	Section* No. 1	Section* No. 2	Section* No. 3
0 - 1	5.3	19.5	5.3	19.5	0.013	0.004	-
1 - 2	9.8	49.0	15.1	68.5	0.015	0.004	0.003
2 - 3	49.8	64.3	64.9	132.8	0.029	0.030	0.018
3 - 4	62.0	65.6	126.9	198.4	0.031	0.032	0.025
4 - 5	67.1	53.8	194.0	252.2	0.025	0.028	0.031
5 - 6	54.7	39.1	248.7	291.3	0.016	0.022	0.026
6 - 7	34.9	26.8	283.6	318.1	0.011	0.014	0.017
7 - 8	24.9	17.8	308.5	335.9	0.007	0.009	0.012
8 - 9	12.0	12.0	320.5	347.9	0.0003	0.004	0.006
9 - 10	9.9	9.1	330.4	357.0	0.0002	0.004	0.005

*Inlet Section No. 1 - Heat Transfer Area = 262 in.^{2}
Weight = 0.66 lb
Length = 6 in.
Mid - Section No. 2 - Heat Transfer Area = 550 in.^{2}
Weight = 1.37 lb
Length = 12.5 in.
Outlet Section No. 3 - Heat Transfer Area = 1468 in.^{2}
Weight = 3.67 lb
Length = 33.5 in.

The chill rate illustrated in the last three columns of the above tabulation shows that energy is removed much more rapidly from the upstream portion of the tube bundle (Section 1) during the early part of the transient period than from the downstream portion of the bundle (Section 3). Later in the transient period, the heat removal from the aluminum is uniform over the length of the bundle. Finally, at the end of the transient period the bulk of the energy removed from the tubes is from the downstream portion of the bundle.

The constant heat-transfer rate from section to section which occurs in the 3 - 5 second time interval implies a linear variation in gas temperature from inlet to outlet during this brief portion of the transient period. For all other time periods, a non-linear variation in gas temperature across the test section would exist.

By comparing the two columns of figures, which present cumulative Btu's involved in the energy exchange between the gas and test piece, it may be seen that there is about a one-second thermal lag in the heat extracted from the test piece. This is believed to be the time required to establish the pseudo steady-state thermal gradient across the tube wall.

While the heat-exchange pattern discussed above was obtained from tests of an aluminum tube bundle, it is believed that the data are representative of the transient heat-transfer effects which take place in a graphite core, since the thermal characteristics (heat capacity, chill area, and material conductivity) of the two test pieces are so much alike.

It is to be noted that the aluminum test section was better insulated from its surroundings in test D-111-LC-10 than in any of the previous tests. (See Section IV,D.) The effectiveness of the additional insulation (as added to the upstream and downstream plenum walls) is illustrated by the fact that the 1/8-in. aluminum wall of the test fixture chilled (per Tw-6 recording) only 30°F in 20 seconds compared to 140°F in 20 seconds in Test D-111-LC-9. Thus, more meaningful heat-transfer data may be obtained from the records of this, the final test on Test Piece No. 2, than from previous tests.

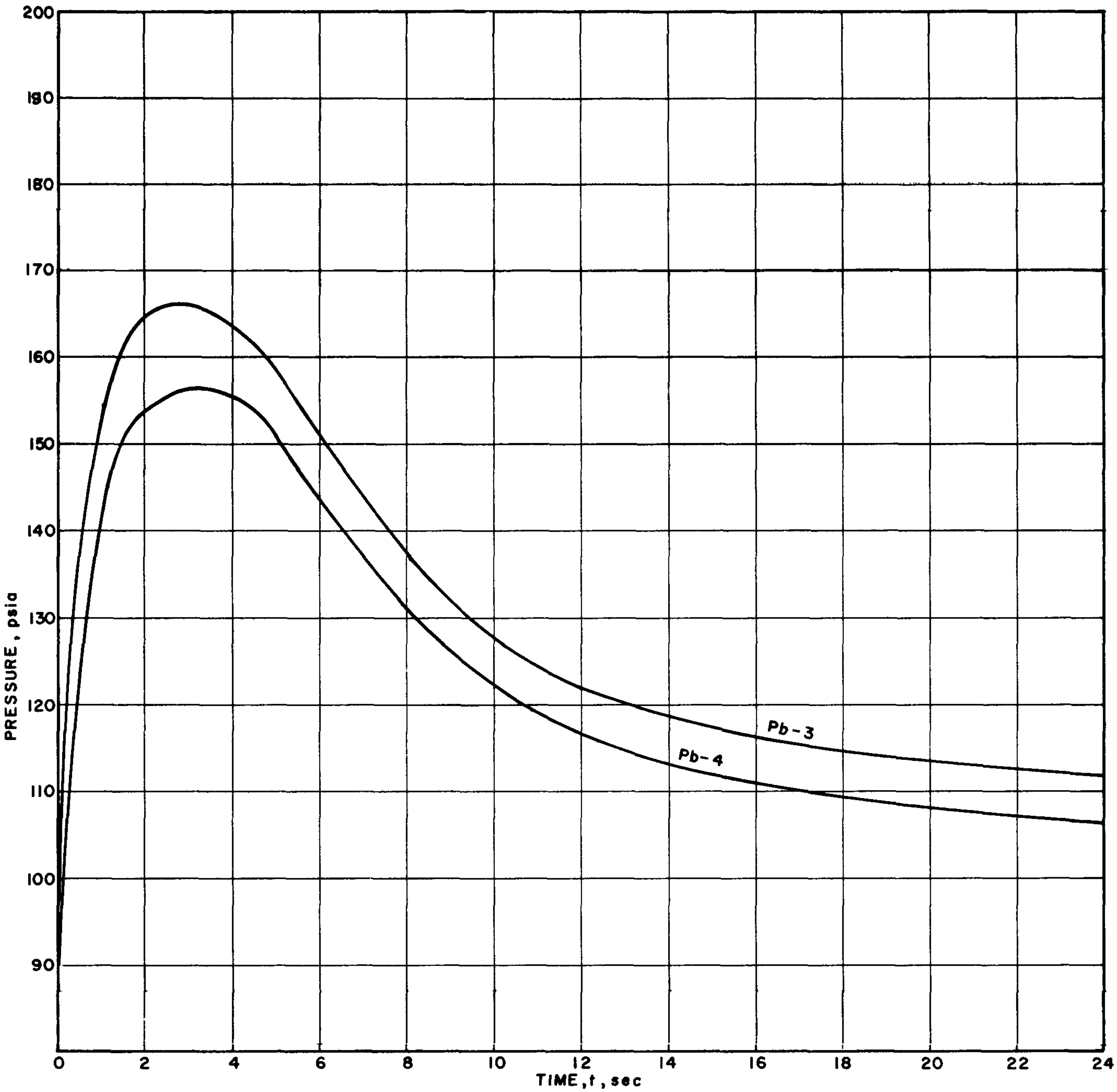

Figure 16

Test Parameters
Inlet and Outlet Pressure
Test D-111-LC-10

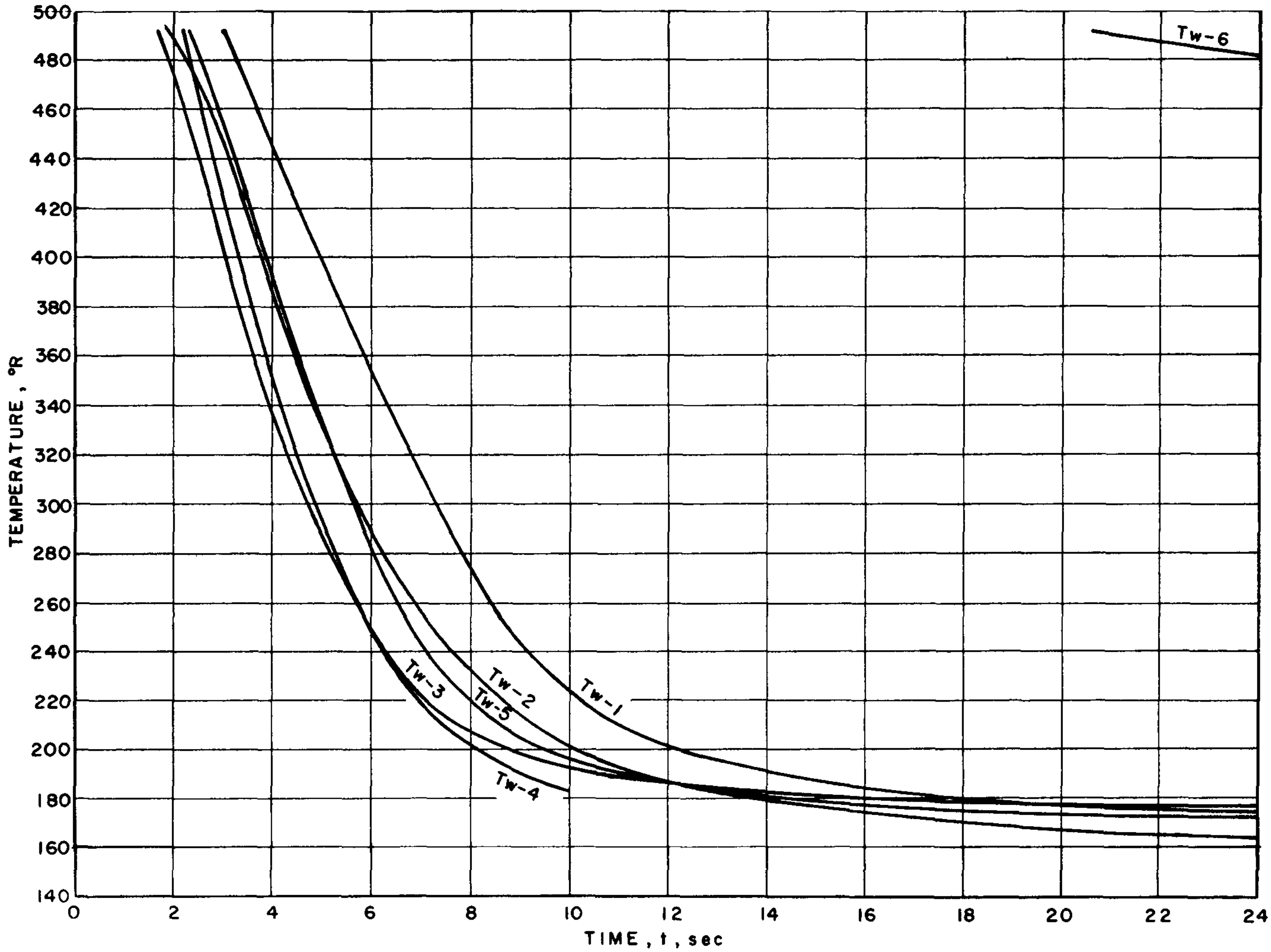

Figure 17

Test Parameters — Wall Temperature
Test D-111-LC-10

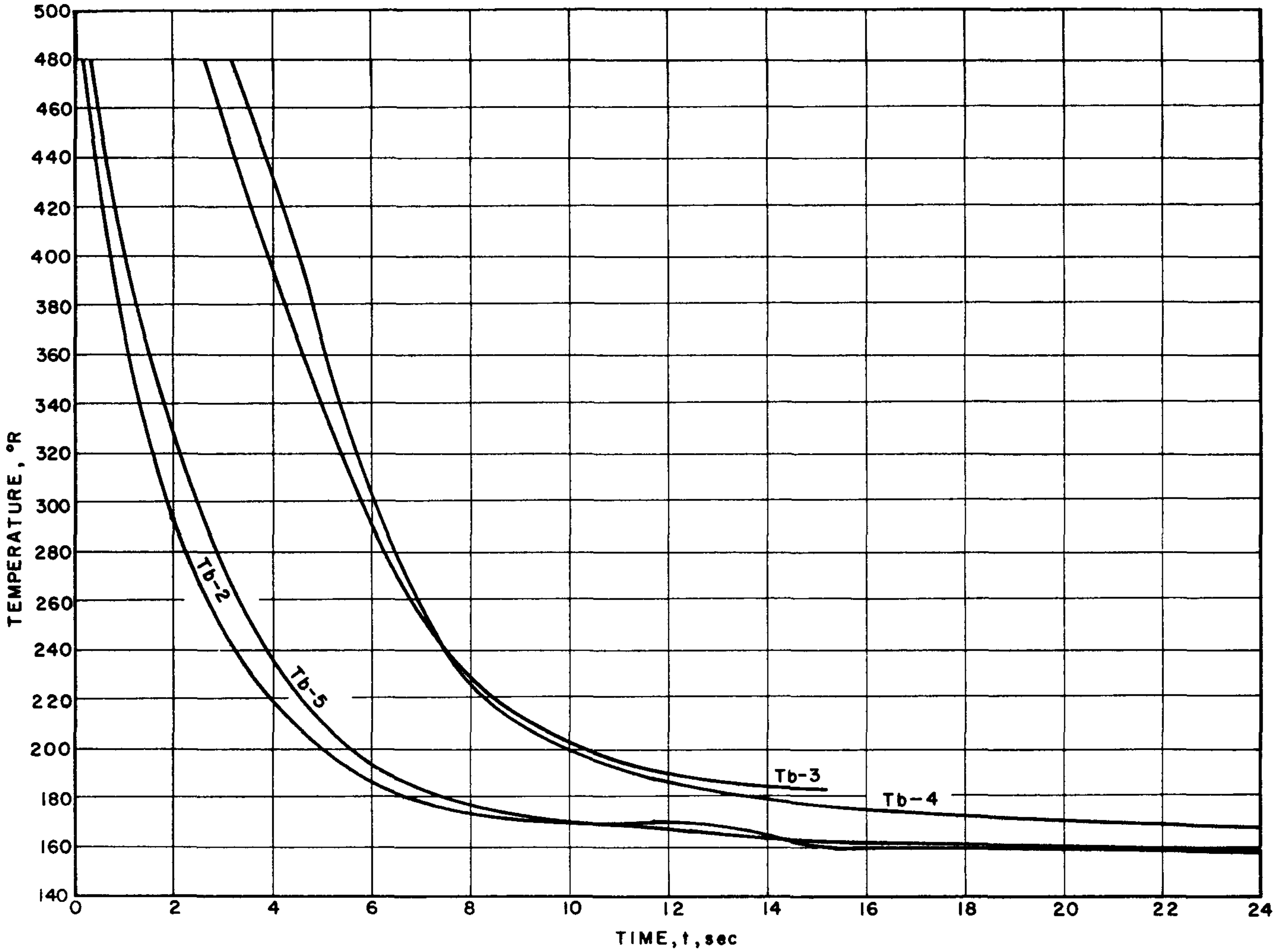

Figure 18

Test Parameters
Inlet and Outlet Temperature
Test D-111-LC-10

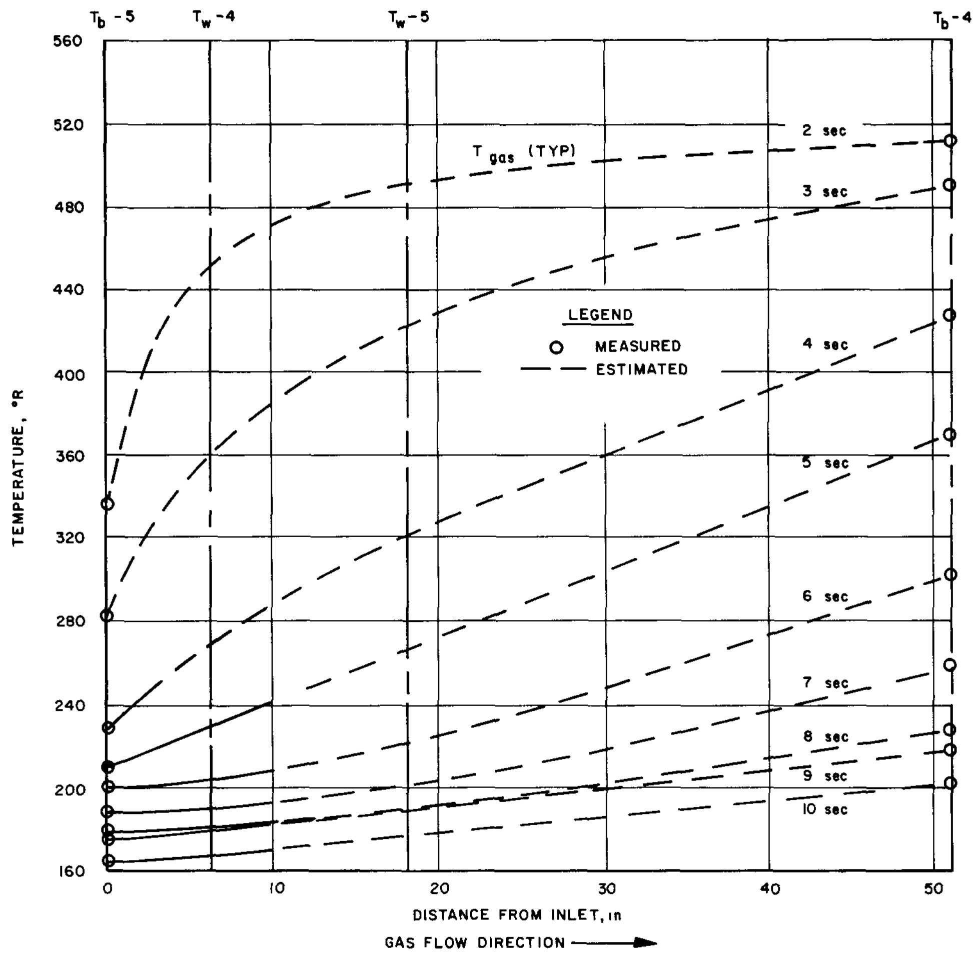

Figure 19B

Gas Temperatures

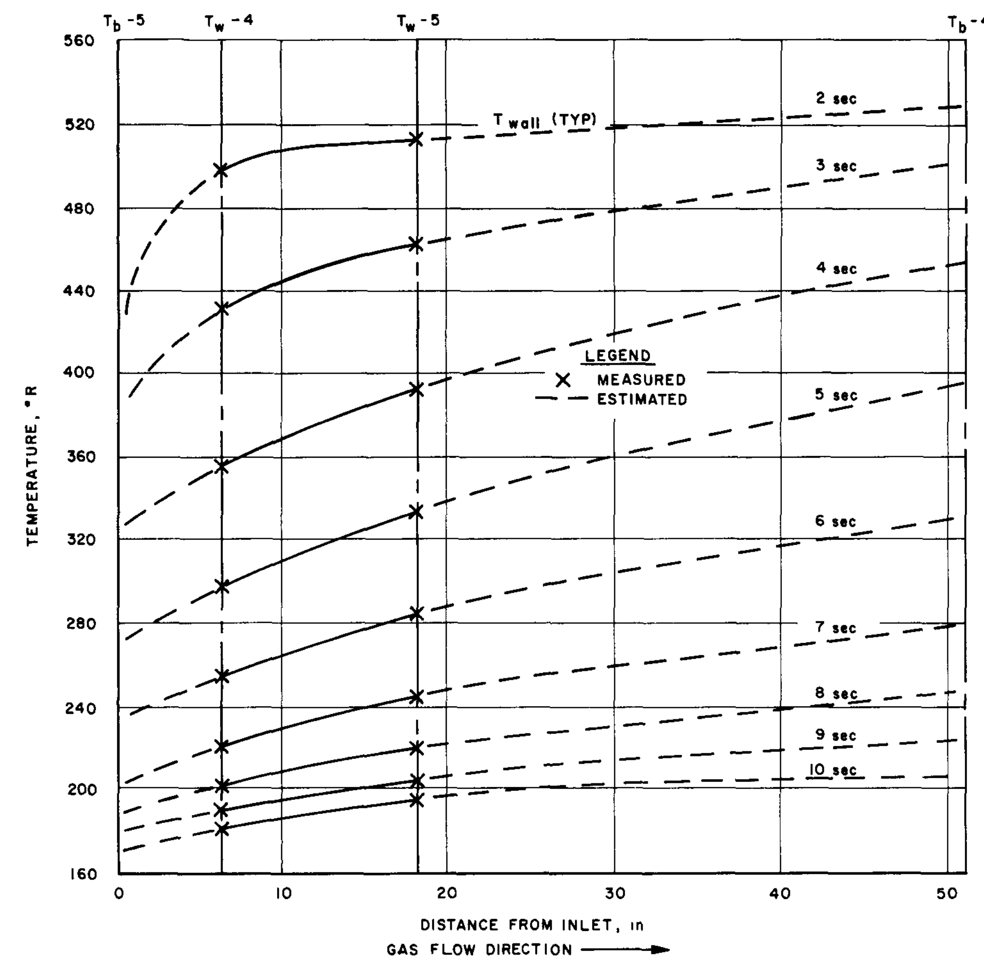

Figure 19A

Wall Temperatures

Figure 19A and 19B

Test Parameters
Relation Between Wall and Gas Temperature

[redacted]

3. Aluminum Test Piece No. 3

Aluminum test piece No. 3 was instrumented with No. 24 wire I.C. thermocouples attached with plastic tape in the locations noted in Figure 11. Test D-111-LC-11 was performed under conditions duplicating those of Test-10.

Figure 20 presents the timewise variation in wall temperatures at various positions across the tube bundle. Tw-1, -2, and -4 were recorded on an oscillograph, and Tw-3 and -5 were recorded on L & N recorders.

Figure 21 presents the timewise variation of gas temperature at the inlet and outlet of the test section. Tb-4 and -5 were recorded on an oscillograph, and Tb-2 and -3 were recorded on L & N recorders.

Figure 22 presents the timewise variation of pressure at the inlet and outlet of the test section.

The thermal lag in a radial and axial direction experienced in this test follow exactly the same pattern as that recorded in Test-10 of aluminum test piece No. 2. The wall temperature measurements indicate that the outer tubes of the bundle (Tw-1 and Tw-2) thermally lag the central tubes (Tw-3, -4 and -5) and the mid-section of the tube bundle (Tw-1 and -5) thermally lags the inlet section (Tw-2, -3 and -4) of the tube bundle. The degree of thermal lag in this test piece appears to be greater than that of the lighter aluminum test piece No. 2.

The pressure drop across the tube bundle is about twice that of the aluminum test piece No. 2. This is the result of a flow area which is about 92% of that of the smaller aluminum bundle, and the fact that the average gas temperature within the bundle is higher during the transient period.

The large amount of heat energy added to the H_2 gas is indicated by the difference between inlet and outlet gas temperature at any particular time. It was expected that more energy would be added to the H_2 gas by this heavy aluminum test piece than by the graphite test piece. This was confirmed by the results of the test program. The significance of this difference in heat exchange is discussed under Section VII,A,3.

[redacted]

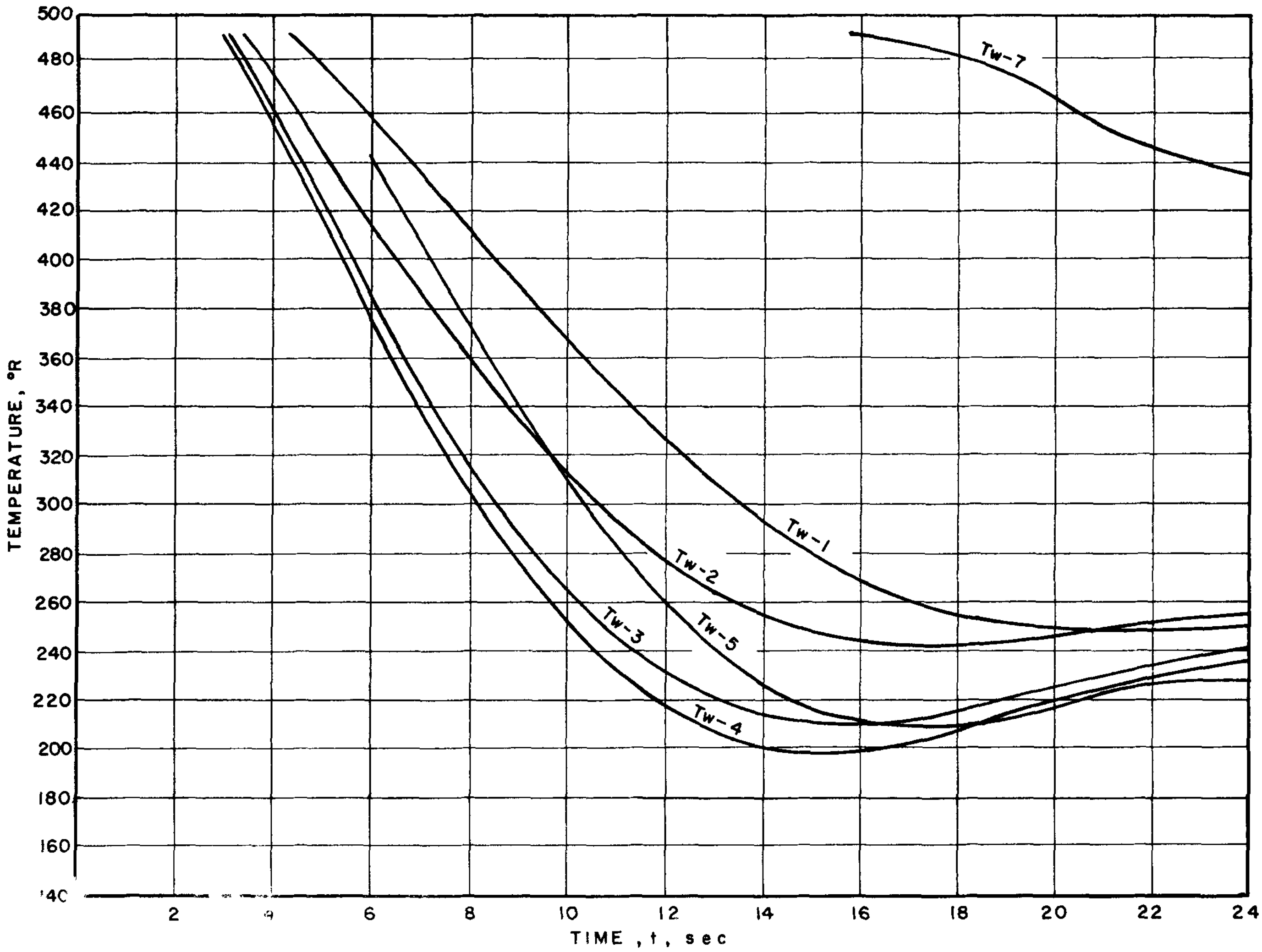

Figure 20

Test Parameters — Wall Temperature
Test D-111-LC-11

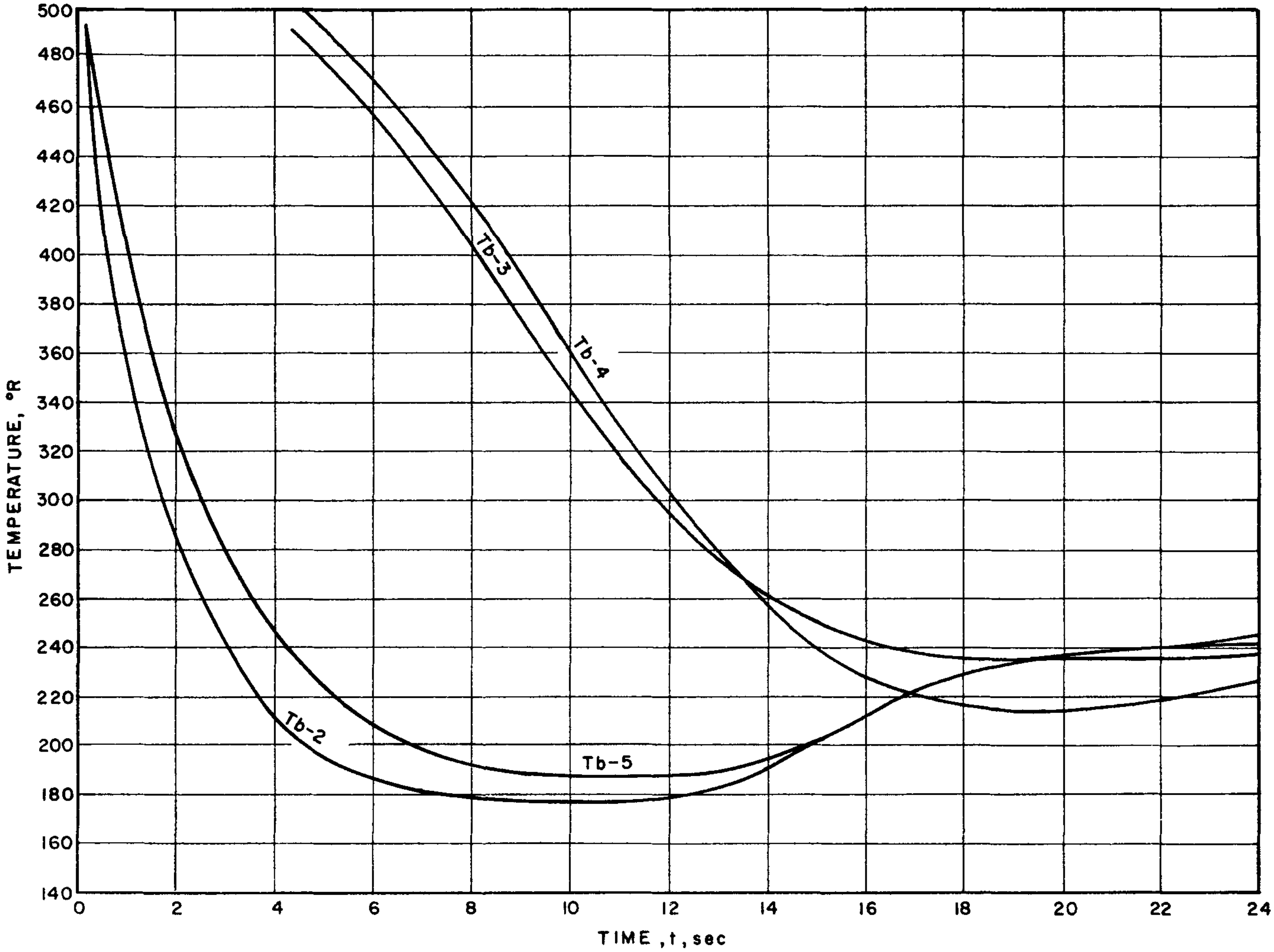

Figure 21

Test Parameters
Inlet and Outlet Temperature
Test D-111-LC-11

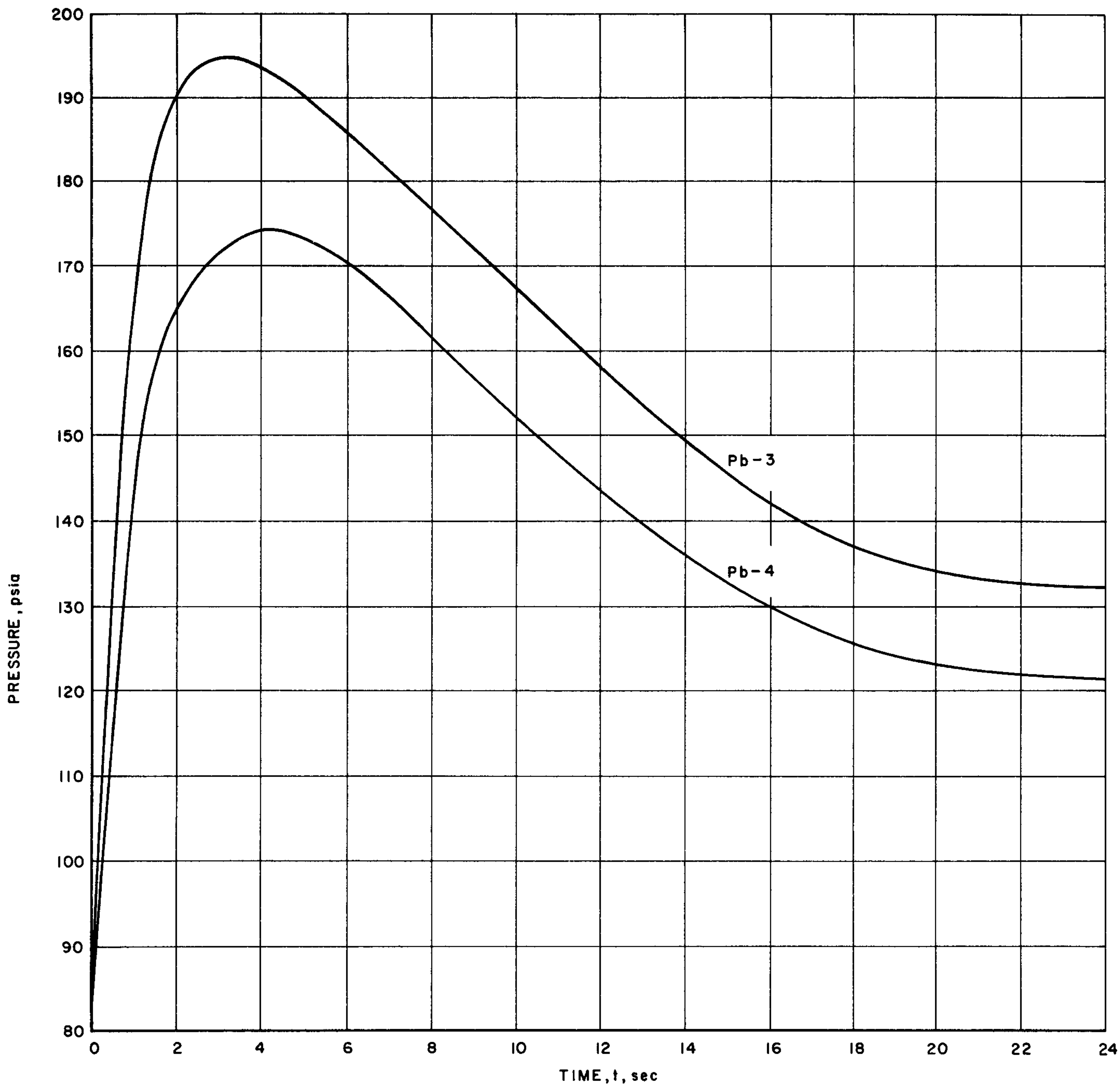

Figure 22

Test Parameters
Inlet and Outlet Pressure
Test D-111-LC-11

[redacted]

E. EVALUATION OF THERMOCOUPLE RESPONSE

1. Aluminum Tube

Upon completion of Tests D-111-LC-6 to 9, it was apparent that the difference in chill rate of the aluminum in Tests 6 to 8, inclusive, and Test-9 could most likely be explained by a difference in the response times of the different wire size thermocouples used in the tests. Accordingly, a brief investigation was carried out to determine the difference in chill rate which would be indicated by thermocouples mounted on an aluminum tube when different wire sizes and mounting techniques were employed.

The test piece was a tube of aluminum (1-in.-OD x 0.049-in.-wall x 12-in.-long) to which were attached five I. C. thermocouples at points equidistant from the end of the tube. The thermocouple wires were connected to an oscillograph through a melting ice cold junction. The test procedure simply involved immersing the tube in a LN_2 bath and recording the output of each thermocouple on the oscillograph. The response time of the various thermocouples is indicated below.

T. C. No.	Wire Size	Bonding Agent	Chill Time - Seconds		
			Amb. to 32^oF	32^oF to -80^oF	Amb. to -80^oF
1	No. 24	Tape	3.4	10.6	14.0
2	No. 16	Tape	6.5	16.4	22.9
3	No. 30	Tape	2.9	9.2	12.1
4	No. 24	Epon	7.1	15.9	23.0
5	No. 16	Epon	7.6	16.0	23.6

The long response times indicated in the tabulation above, are the result of poor heat transfer from the boiling LN_2 to the aluminum. These response times are only useful in providing comparative data for the various thermocouple installations. The data follow the general rule that the mass of the thermocouple junction or bead dictates its response, and that the smaller the mass the faster the response.

The No. 24 and 30 wire size thermocouples, mounted with plastic tape, chilled at approximately twice the rate of a No. 16 wire thermocouple mounted either with Epon 921 resin or plastic tape. This same No. 24 wire thermocouple

[redacted]

mounted with tape chills at about twice the rate of a No. 24 wire thermocouple mounted with Epon resin. Although the No. 30 wire thermocouple indicated the highest response in the experiment, the fact that No. 24 wire is nearly as responsive and is a more practical size to install on a specimen, suggested its use in future tests of the aluminum tube bundle, (i.e., Tests D-111-LC-10 and -11).

2. Graphite Tube

For cold flow experiments with graphite, it is important to know the effect of wire size upon the response of thermocouples mounted on graphite, although it can generally be postulated that the finer the wire, the faster the response.

The relative response of various size thermocouples taped to graphite was determined by immersing the test piece in LN_2 and recording the output of each thermocouple on an oscillograph.

The test piece was a tube of normal graphite (3/4-in.-OD x 1/8-in.-wall x 12-in.-long) to which were attached three thermocouples (wire sizes No. 16, 24, and 30) at points equidistant from the ends of the tube.

Two tests were performed using the procedure developed in tests of thermocouples on an aluminum tube. The response time of the various thermocouples is indicated in the tabulation below.

Test No.	TC No.	Wire Size	Bonding Agent	Chill Time - Seconds		
				Amb. to 32°F	32°F to -80°F	Amb. to -80°F
1	1	16	Tape	0.8	2.0	2.8
1	2	24	Tape	1.60	3.95	5.55
1	3	30	Tape	1.30	3.55	4.85
2	1	16	Tape	1.25	2.60	3.85
2	2	24	Tape	1.85	11.50	13.35
2	3	30	Tape	1.25	10.60	11.85

The difference in chill rates indicated for Tests 1 and 2 is the result of different immersion depths of the graphite tube in the LN_2 bath. The tabulation above indicates that the response of the No. 16 wire thermocouple is faster than that of either the No. 24 or 30 wires. These test data are completely contrary to the results which would be expected with thermocouple wires of different size. No explanation is attempted for this data. It is presented only to indicate that additional tests of similar type instrumentation which might be used in the CFDTS would be warranted.

It is to be noted that Tests D-111-LC-2 thru 5 were conducted with No. 16 thermocouple wires, the most responsive of the three sizes tested.

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SECTION VII

DATA ANALYSIS

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VII. DATA ANALYSIS

A. SUBSTITUTE REACTOR MATERIAL FOR CFDTS

1. Factors Involved in Simulation

In cold-flow tests of a core, H_2 gas at low temperatures passes through an ambient-temperature core material and extracts heat energy. For simulation of graphite by a substitute material, the amount of energy transmitted from each material to the H_2 gas should be the same. Demonstration of this fact (by a measure of the total enthalpy change in the H_2 gas as it passes through the test piece) will prove simulation. At the same time the Btu's removed from the test core (as determined from enthalpy changes in the material) should be equivalent to the heat added to the H_2 gas. This will be reflected in a certain rate of chill for each test piece.

The factors to be considered in designing a test piece which will thermally simulate graphite are its thermal storage capacity (product of weight and specific heat) and the heat transfer or chill area. In a thin-walled test piece, (considering wall thicknesses in the range of 0.020 to 0.038-in. for aluminum and graphite respectively), it is assumed that there will be essentially no temperature gradient across the wall, during the major part of the chill period; hence, the diffusivity of the material should not be the controlling factor in the rate of energy exchange with the H_2 gas. If two test pieces are considered (i.e., graphite and aluminum) and the relationship of $\frac{\text{specific heat x weight}}{\text{heat transfer area}}$ is the same for each test piece, thermal simulation should theoretically be achieved. The tabulation below shows the near identity of this parameter for the graphite and aluminum test piece No. 2, and the large difference in the values of this parameter for the graphite and aluminum test piece No. 3.

Test Piece Number	Material	Weight lb	Ave C_p Over Temp. Range Btu/lb ^{o}R	Area-A	$\frac{\text{Wt. x } C_p}{A}$ Btu/in.^{2} ^{o}R
1	Graphite	9.3	0.11	1850	5.55×10^{-4}
2	Aluminum	5.7	0.19	2280	4.75×10^{-4}
3	Aluminum	14.4	0.19	1970	13.9×10^{-4}

[redacted]

The parameter $\frac{Wt. \times C_p}{A}$ is a term which is indicative of the rate of chill or heat transfer rate during cold flow. It would be expected that aluminum test piece No. 2 would have a slightly faster chill rate than the graphite section for the same weight flow of H_2 gas through the piece. Aluminum test piece No. 3 should chill at a rate about half that of the graphite piece.

[redacted]

2. Accuracy of Analysis

Section IV,D discussed the methods employed to thermally isolate the test piece throughout the test series. In particular, the insulation of the inlet and outlet plenum walls from the H_2 gas was found to be important if one hoped to equate the energy transferred from the test piece to that absorbed by the H_2 gas.

In Tests D-111-LC-2 to 5, of the graphite test piece, no thermal insulation of the plenum walls was provided, based on the theory that the energy exchange between the H_2 gas and the test fixture would be so small during the first few seconds of the transient period as to not appreciably affect the results, since only comparative data are required to prove simulation. The Tw-6 recording of inlet plenum wall temperature in these tests showed that the wall starts to chill about 4 to 5 seconds after gas is introduced into the test section. Since, the first 6 to 7 seconds of the test is the period of interest in demonstrating simulation of test pieces, the measured change in the enthalpy of the H_2 gas during the transient period should be relatively unaffected by external heat sources.

In Test D-111-LC-10 of aluminum test piece No. 2, and Test D-111-LC-11 of aluminum test piece No. 3, good thermal insulation of the plenum walls was provided. Accordingly, in these two tests it was possible to equate the energy transferred from the test piece to that absorbed by the H_2 gas with reasonable accuracy.

3. Degree of Thermal Simulation

The data from Test D-111-LC-3 were considered to be the most representative of those obtained in the four tests of the graphite test piece. The data from Test D-111-LC-10 are considered to be the only accurate information obtained from the five tests of aluminum test piece No. 2. The data from Test D-111-LC-11, the only test performed with aluminum test piece No. 3, are considered to be the most accurate of any of the data obtained in the program. Pressures, wall temperatures, and gas temperatures from these three tests are presented as figures in this report and are the basis for the analyses which were performed.

Based upon the inlet and outlet gas temperature measurements in these three tests, the enthalpy change in the H_2 gas as it passed through the test piece was determined over one-second intervals. Based upon a constant flow rate of gas through the test piece ($\dot{W} \approx 0.10$ lb/sec), the Btu addition to the gas during each second of the start transient period (10 seconds) was determined. Since normal hydrogen was used in these tests, the analysis was based on the thermodynamic properties of normal hydrogen (as taken from NBS Technical Note No. 120, by John W. Dean). It is of interest that the specific heat of normal hydrogen is approximately 20% lower than that of para-hydrogen over the temperature range (200 to 400°R) covered by these tests, and that a considerable error would have resulted from the use of para-hydrogen properties.

The cumulative Btu addition to the H_2 gas for the first ten seconds of each test is shown in Figure 23. Proof of the thermal simulation of graphite by aluminum test piece No. 2 is illustrated in this figure by the fact that, to 6 seconds, a total of 310 Btu were added to the H_2 gas by each of the two test pieces. Thereafter, the data indicate that about 60 more Btu are added to the H_2 gas (in the 6 to 10-second period) by the graphite piece than the aluminum piece. It is believed that these additional Btu represent heat exchange from the test fixture rather than from the graphite.

The Btu addition to the gas from aluminum test piece No. 3 is a factor of 1.55 greater than that added by the graphite piece. Thus, it is shown that the heavier aluminum section does not provide thermal simulation of the graphite piece, and substantiates the hypothesis that the parameter, $\frac{C_p \text{ x Weight}}{\text{Cooling Area}}$, controls the rate of heat exchange between these thin-walled sections and the H_2 gas. The identity of this parameter for test pieces Nos. 1 and 2 has previously been discussed.

Figure 23 also presents the Btu extracted from the material of the three test pieces by the gas. Based upon the change in temperature of the material over one-second intervals during the 10-second transient chill period, and using appropriate values of specific heat over the temperature range, the cumulative Btu extraction from each test piece by the H_2 gas was calculated. In the case of the graphite test piece, the agreement between the heat extracted from the test piece and the heat added to the gas is generally poor. In the case of the aluminum test pieces, however, (which were much better insulated from the wall of the test fixture), excellent agreement is obtained between the number of Btu extracted from the material and the number added to the gas.

Examination of the data in Figure 23, indicates that a thermal lag is involved in extracting the heat energy from the material, whether it be graphite or aluminum; this is believed to reflect initial temperature gradients across the wall. A part of this thermal lag, however, is believed to be caused by limitations in the response of the thermocouples. The thermal lag of the 0.020-in.-wall aluminum tubes appears to be less than that of the thicker graphite (distance from the edge of the outer hole to the outside of the hexagon test piece is 0.038 in.). If the cumulative Btu curves (representing heat extraction) from the material are adjusted for thermal lag, it can be seen that the rate of Btu addition to the gas and extraction from the material are about the same over the first 6 seconds of the transient period for the graphite and the aluminum No. 2 test pieces. It should be noted (from Figure 23) that reasonable simulation occurs for 9 seconds. This is well beyond the expected chill-down duration of CFDTS.

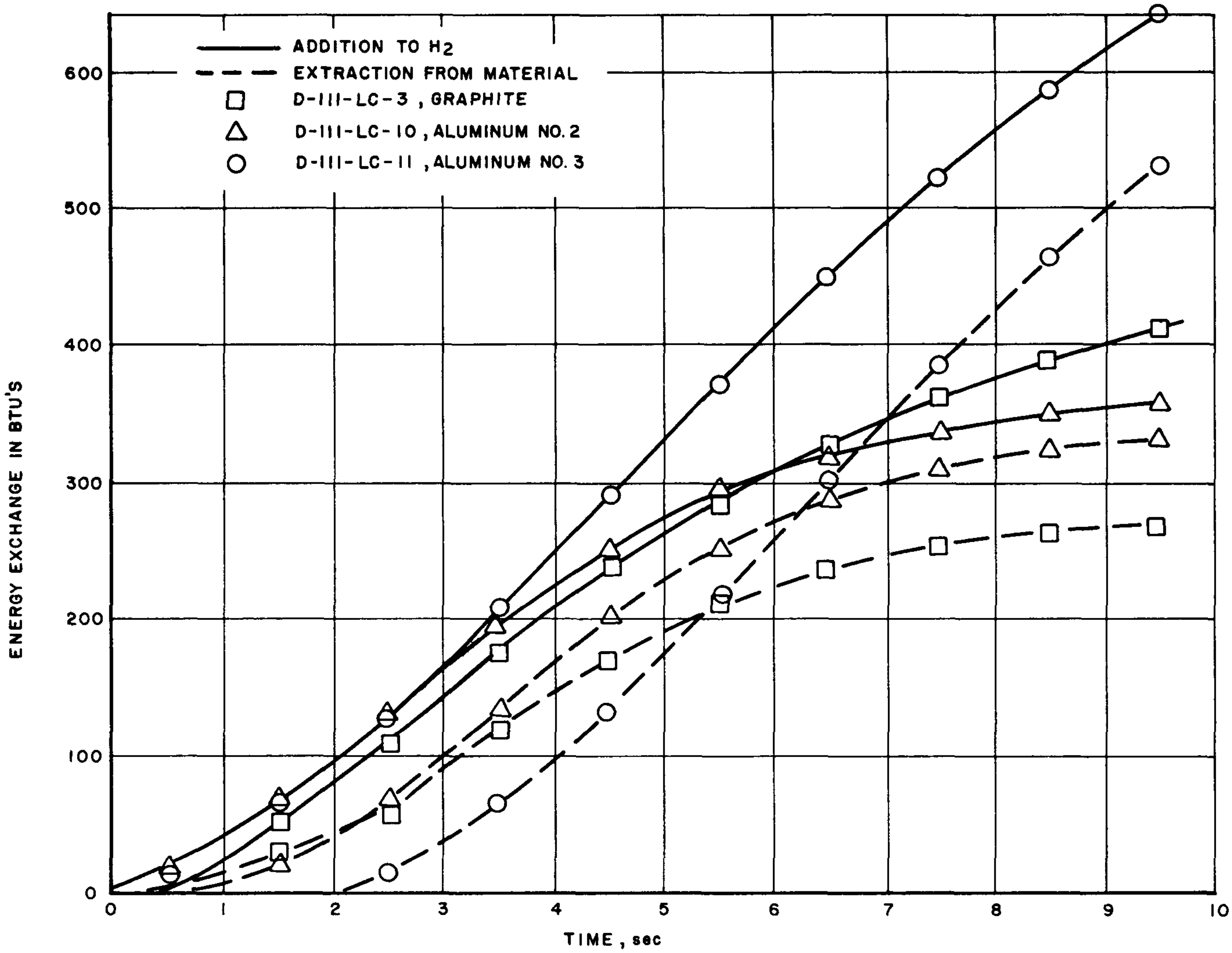

Figure 23

Energy Exchange Data
of H_2 Gas and Test Pieces

B. COMPARISON WITH ANALOG MODEL OF NERVA ENGINE

Pertinent data from tests of the graphite piece were compared with similar type data developed in a system start-transient study made on the power-range analog-computer model, and reported in REON Report 2710. Data of interest in this comparison are timewise variations in flow rates, gas pressures, and temperatures at the inlet and outlet of the core, and temperature of the core material during its chill-down.

Figure 12 (which is again reproduced adjacent to Figure 24 for comparative purposes) is a plot of flow, pressure [inlet and outlet], and temperature [gas inlet, gas outlet, and wall] during a portion of the start transient, as determined in the analog-computer model study. This data provided the basis for establishing flow rates, pressure levels, and temperature ranges in the subject program, and was discussed at some length in Section VI, A.

Figure 24 is a plot of flow, pressure, and temperature data, which were obtained experimentally in Tests D-111-LC-2 to -5, inclusive. By comparison of the information presented in Figures 12 and 24, it can be seen that the timewise variations of experimental and computed core outlet (chamber) temperature and graphite wall temperatures are in reasonable agreement over that part of the transient period for which the expected inlet gas temperature to the core could be duplicated in test.

The chill rate of the cluster in the test series was found to be higher than that reported in REON Report 2710. This is most likely the result of performing these tests at a constant flow rate rather than at the variable flow indicated by the analog computation.

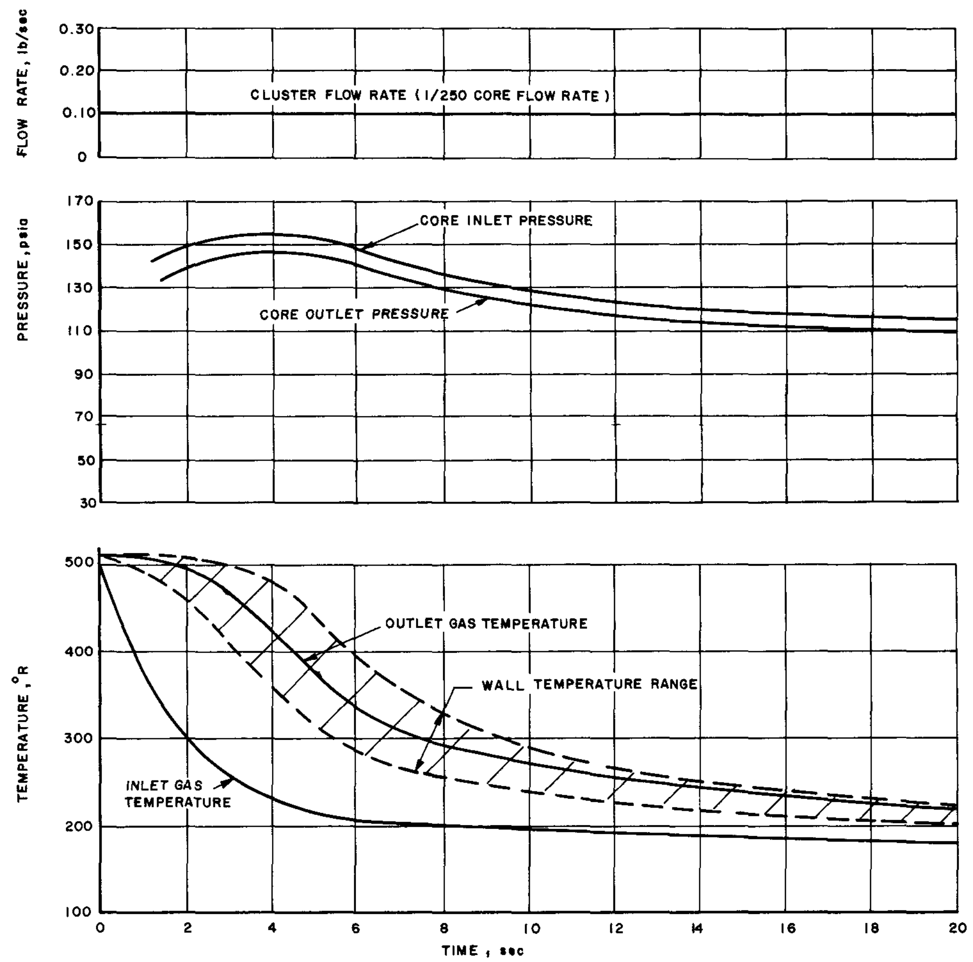

Figure 24

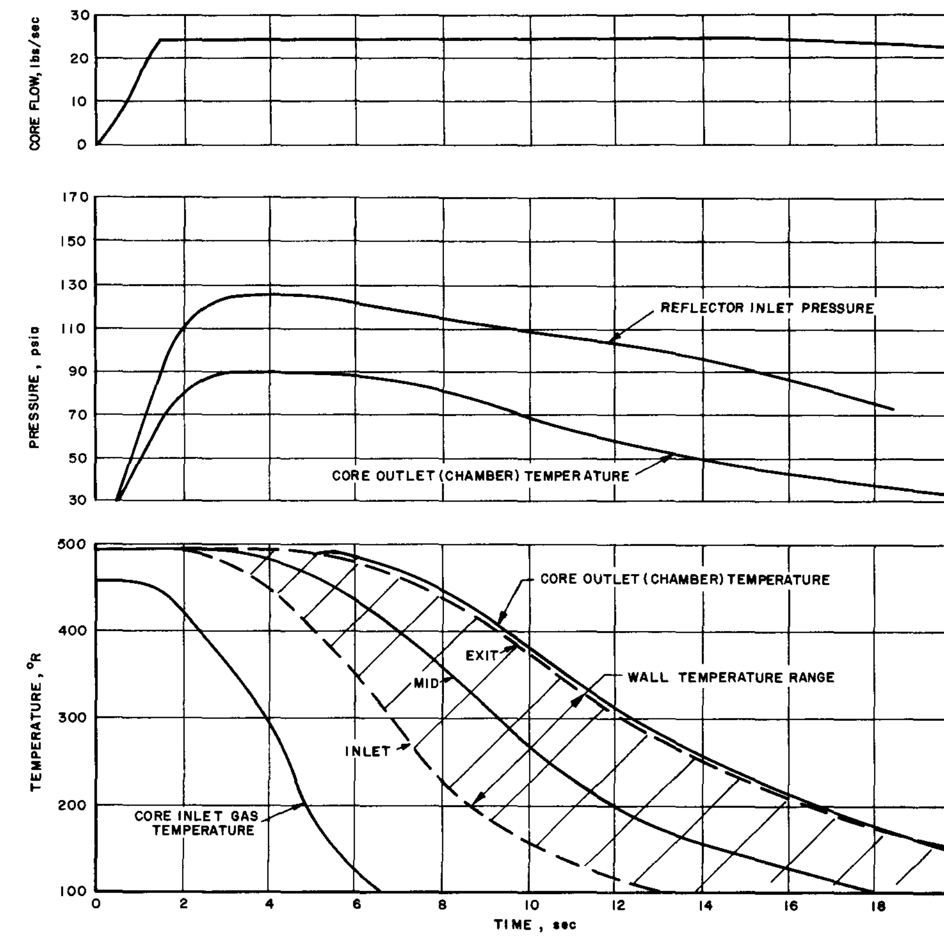

Figure 12

(as previously shown on page 42)

Start-Transient Data
Flow, Pressure, and Temperature
As a Function of Time

Figure 24

Test Parameters
Flow, Pressure and Temperature
Tests D-111-LC-2 through 5

[redacted]

C. PRESSURE DROP AND FRICTION FACTOR

Figure 25 presents a comparison of the pressure drops across the graphite and the aluminum test piece No. 2, based upon data obtained in Tests D-111-LC-5 and -10, respectively. In the case of each test piece, the pressure drop varies with time as a result of pressure and temperature changes in the system during the transient period of interest. The pressure drops for the two test pieces are about equal and range from initial values of about 10 psi (500°R gas) to final values of about 5 psi (200°R gas).

The pressure drop during cold flow across a real core would be slightly higher than these values as a result of the orificing of each passage. In any case, in CFDTS tests the pressure drop across the core (whether prototype or simulated) is so small in comparision with the total pressure drop in the system that the thermal characteristics of the system should be relatively insensitive to variations in the magnitude of core pressure drop.

The data from Tests D-111-LC-2 through -5 were analyzed to establish the friction factor experienced in H_2 flow through the graphite cluster. Pressures and temperatures were measured at points in the 1-in.-dia line immediately upstream and downstream of the test fixture. In Test D-111-LC-5, a Pace differential pressure gage was installed across the test section to provide a check on the accuracy of the pressure drop, which was calculated as the difference between two absolute pressures. The pressure drop data obtained by these two methods were within 15% of each other. Hence, the pressure drop data of Tests D-111-LC-2 thru -4, determined by the difference in two absolute pressure measurements, is believed to be reasonably accurate.

The special losses at the inlet and outlet of the test piece and at the inlet and outlet of the plenum volumes (considered to be a total of three velocity heads) were added to the momentum loss across the test section. The difference between this sum and the measured pressure drop was considered to be the frictional loss. The data from each test were evaluated at about 4-second intervals to provide a friction factor over a fairly wide range of Reynold's numbers.

[redacted]

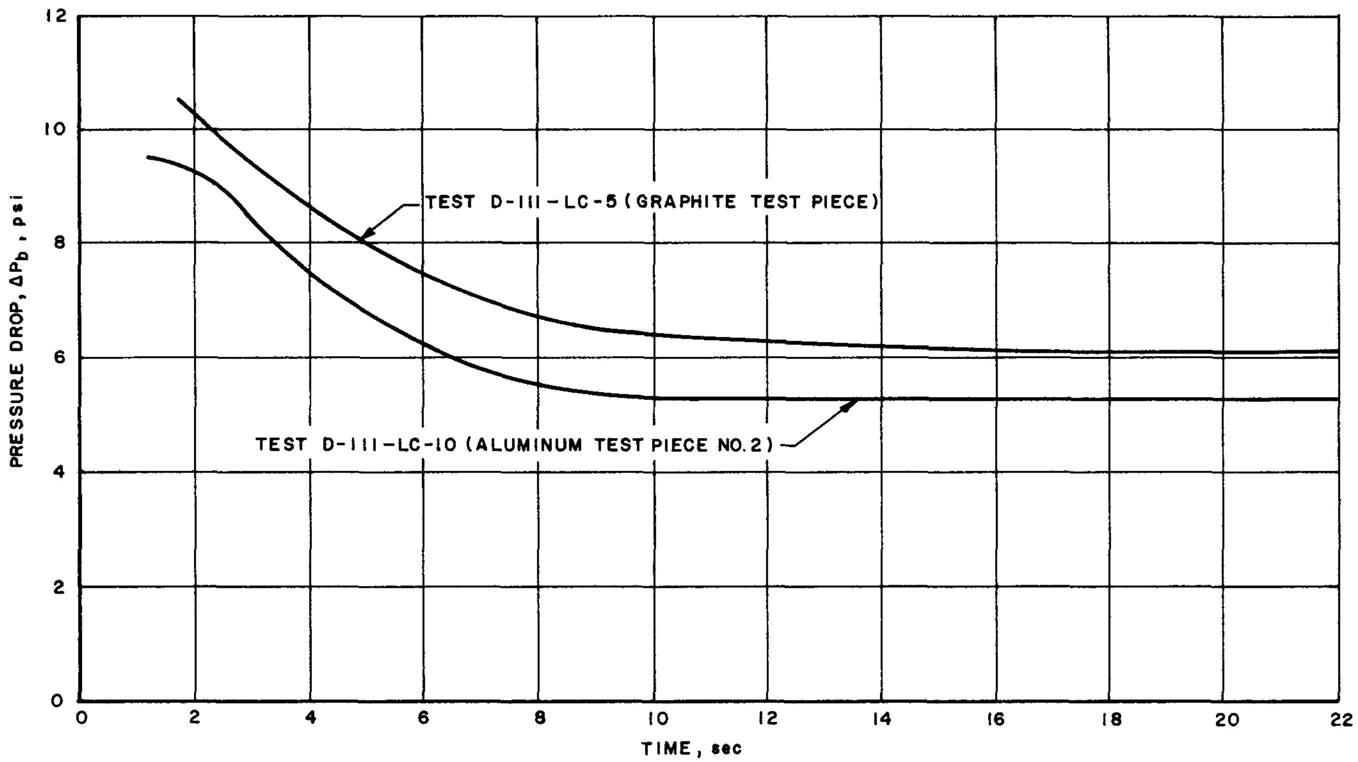

Figure 25

Pressure Drop Variation
in Cold Flow Test Pieces

Table 1 presents the fundamental data leading to the evaluation of the friction factor. The data may be summarized as follows:

Test Conditions

Temperature range:	450 - 190°R
Pressure range:	150 - 105 psia
Reynolds Number range:	25700 - 44800
Fluid:	H_2 gas

Friction Factor for Unfueled Graphite Element

Range of values:	0.0235 to 0.0438
Average "f":	0.034
Relative roughness $(\frac{e}{D})$ of graphite:	0.006

TABLE 1

FRICTION FACTOR FOR FLOW OF H_2 GAS THROUGH GRAPHITE ELEMENT

Test No.	Time sec	$\dot{W}$ lb/sec	$P_{avg.}$ psia	$T_{gas\,avg.}$* °R	RN	ΔP Total psi	ΔP Momentum psi	ΔP Special Losses psi	ΔP Friction psi	f**
D-111-LC-2	2.9	0.00085	152	388	27,200	10.7	0.25	1.10	9.35	0.044
	5.4	0.00085	147	284	32,300	7.7	0.15	0.84	6.70	0.041
	8.4	0.00085	129	247	39,000	6.9	0.12	0.88	5.90	0.035
	13.4	0.0085	121	226	41,200	7.0	0.09	0.90	6.00	0.036
	18.4	0.00085	117	233	39,800	7.0	0.04	1.00	5.96	0.034
D-111-LC-3	3.0	0.00093	146	450	28,000	9.8	0.32	1.66	7.82	0.024
	5.5	0.00091	142	352	32,500	7.9	0.26	1.25	6.39	0.026
	8.5	0.00089	128	266	38,500	6.0	0.16	1.03	4.81	0.024
	10.5	0.00087	123	247	40,000	7.0	0.15	0.97	5.88	0.032
	13.5	0.00085	117	223	41,200	7.0	0.11	0.91	6.00	0.035
	17.5	0.00082	113	219	41,500	7.1	0.08	0.90	6.12	0.030
D-111-LC-4	3.0	0.00082	149	401	26,800	10.7	0.23	1.10	9.37	0.042
	5.0	0.00082	146	327	30,400	8.7	0.18	0.89	7.63	0.040
	8.0	0.00082	132	251	36,600	6.9	0.11	0.69	6.00	0.039
	12.0	0.00082	118	223	40,000	6.1	0.10	0.81	5.19	0.033
	18.0	0.0082	109	197	42,400	6.1	0.08	0.84	5.18	0.033
	24.0	0.00082	105	189	43,600	6.2	0.06	0.81	5.33	0.036
D-111-LC-5	5.0	0.00087	159	359	30,200	8.0	0.21	1.02	6.77	0.032
	10.0	0.00087	132	255	38,800	6.5	0.13	0.89	5.48	0.031
	15.0	0.00087	121	223	42,000	6.2	0.12	0.90	5.18	0.030
	20.0	0.00087	117	202	44,800	6.1	0.11	0.87	5.12	0.032
	25.0	0.00087	113	198	44,800	6.1	0.10	0.89	5.10	0.032

Constants:

Flow Area = 0.0072 in.^{2}
Hole Dia = 0.008 ft
Element "L"= 4.33 ft

*Adjusted arbitrarily from record of inlet and outlet gas temperatures according to the magnitude of the temperature difference.

**Friction formula:

$$\Delta P_{total} = \frac{144\,\dot{W}}{2\,g\,A^2}\left\{\underbrace{\left[\frac{1.0}{\rho\ out} - \frac{1.0}{\rho\ in}\right]}_{momentum} + \underbrace{\left[\frac{1.5}{\rho\ out} + \frac{1.5}{\rho\ in}\right]}_{special} + \underbrace{f/\rho_{avg.}\cdot\frac{L}{D}}_{friction}\right\}$$

D. HEAT TRANSFER COEFFICIENT

Both local and over-all experimental heat-transfer coefficients were evaluated for each test section. Data from transient and pseudo-steady-state conditions were analyzed. Analysis of all pertinent data resulted in a heat-transfer coefficient of about 0.00073 Btu/in.^{2}-sec-$^\circ$R, which is about half that calculated from McAdams Formula under comparable conditions This is considered to be a reasonable correlation for H_2. (See Section VII,D,4.)

1. <u>To Graphite</u>

The data of Tests D-111-LC-2 to 5 inclusive were analyzed to determine the average gas-side heat-transfer coefficient between the H_2 gas and the graphite test piece. The average wall temperature of the test piece was based on measured values. The average gas temperature was arbitrarily established as a value falling between measured inlet and outlet gas temperatures, and as a value closer to the outlet temperature when the gas temperature change across the test piece was large. The difference between the average wall temperature and the average H_2 gas temperature was related to the overall heat addition to the H_2 gas (as determined by its enthalpy change as it passed through the test section) to establish the average coefficient at one second intervals It was assumed that the temperature gradient across the thin wall was so small that it could be neglected in coefficient calculation.

The heat-transfer coefficient varied from 0.00052 to 0.00091 Btu/in.^{2}-sec-^{o}R over the temperature range from 510 to 220^{o}R. Table 2 presents the basic information leading to the calculation of these values.

TABLE 2

HEAT TRANSFER COEFFICIENT BETWEEN H_2 GAS AND GRAPHITE

Time	T_{gas} avg.* °R	T_{wall} avg. °R	ΔT avg. °R	q Btu/sec	Surface Area-A in.^{2}	q/A Btu/in.^{2}/sec	"h" Btu/in.^{2} sec °R
2.0	455	510	55	60.4	1850	0.0318	0.00058
3.0	410	477	67	65.9		0.0346	0.00052
4.0	370	420	50	59.3		0.0312	0.00063
5.0	340	375	35	58.0		0 0305	0.00087
6.0	308	340	32	50.1		0.0263	0.00082
7.0	282	310	28	40.1		0.0211	0.00076
8.0	262	290	28	35.1		0.0185	0.00066
9.0	252	275	23	32.4		0.0170	0.00074
10.0	245	262	17	29.7		0.0156	0 00091
11.0	236	252	16	26.8		0.0140	0.00087
12.0	230	246	16	24.0		0.0126	0.00079
13.0	225	240	15	21.1		0.011	0.00074
14.0	220	238	18	21.1	1850	0.011	0.00074

*Adjusted arbitrarily from record of inlet and outlet gas temperatures according to the magnitude of the temperature difference.

2. <u>To Aluminum (Test Piece No. 2)</u>

The data of Test D-111-LC-10 were analyzed to determine the average gas-side heat-transfer coefficient to the aluminum test piece. This test was performed under conditions which permitted the gas and the test piece to be briefly in steady-state thermal equilibrium. Data taken at 20 seconds (Reference Figures 12 and 13) were representative of temperatures and temperature differences during the brief steady-state period. The coefficient calculation, as based on steady-state data, is shown in the tabulation below:

a. Measured Data at 20 Seconds

$T_{gas\ inlet}$	$= 160^{o}R$
$T_{gas\ outlet}$	$= 170^{o}R$
$T_{gas\ ave}$	$= 165^{o}R$
$T_{wall\ ave}$	$= 180^{o}R$
$\dot{W}_{H_2}$ gas	= 0.10 lb/sec
Heat transfer surface area	$= 2280\ in.^2$

b. Calculated Data

Inlet enthalpy of normal H_2	= 615 Btu/lb
Outlet enthalpy of normal H_2	= 640 Btu/lb
Change in specific enthalpy	= 25 Btu/lb
Heat-transfer rate	= 2.5 Btu/sec
Unit heat-transfer rate	$= 0.0011\ Btu/in.^2\text{-sec}$

$$h_g = Q/A \div (T_{wall_{ave}} - T_{gas_{ave}})$$

$$\frac{0.0011}{15} = 0.00073\ Btu/in.^2\text{-sec-}^{o}R$$

The value of the heat-transfer coefficient to aluminum is nearly equal to the heat-transfer coefficient to graphite as shown in Table 2.

3. To Aluminum (Test Piece No. 3)

The data of Test D-111-LC-11 were analyzed to provide a value for the local heat-transfer coefficient from H_2 gas to aluminum. The data (reference Figures 15 and 16) were analyzed at a time 10 seconds after the start of the test. The wall temperature measurements taken from the central tube in the bundle (indicated by Tw-4 and Tw-5) were assumed to be indicative of the temperature of that section of the complete bundle lying between planes 6 and 18.5 inches from the inlet. This particular section of the bundle, with a heat-transfer surface area of 472 sq in., provided the basis for determining a value of heat-transfer coefficient in this test. The change in temperature of the material over a one-second time interval, multiplied by its specific heat and the weight of the section, provided the measure of the Btu extracted from this local section of the tube bundle by the H_2 gas.

a. Measured Data at 10 Seconds

$T_{gas_{inlet}}$ (tube bundle) $= 186^{\circ}R$

$T_{gas_{outlet}}$ (tube bundle) $= 360^{\circ}R$

$T_{gas_{average}}$ (tube section) $= 230^{\circ}R$

The average gas temperature across the particular section of bundle was based upon the assumption that the gas temperature varied linearly along axis of tube bundle, since a constant heat-transfer rate was obtained along the length of tube bundle at this particular time (10 seconds).

Tw-4 $= 250^{\circ}R$

Tw-5 $= 310^{\circ}R$

$T_{wall_{avg}}$ $= 280^{\circ}R$

$\dot{W}_{H_2\ gas}$ $= 0.10$ lb/sec

Heat transfer surface area $= 472$ in.^{2}

b. Calculated Data

Change in wall temperature in 1 sec	$= 30^{\circ}R$
Average specific heat of aluminum	$= 0.170$ Btu/lb-$^{\circ}$R
Weight of aluminum section	= 3.46 lb
Heat-transfer rate	= 17.6 Btu/sec
Unit heat-transfer rate	$= 0.037$ Btu/in.^{2}-sec
$h_g = Q/A \div (T_{wall_{avg}} - T_{gas_{avg}}) = \frac{0.037}{50}$	$= 0.00074$ Btu/in.^{2}-sec-$^{\circ}$R

The local value of the heat-transfer coefficient to aluminum shown above is about the same value as the overall coefficient calculated for the graphite test piece (Reference Table 2) and aluminum test piece No. 2.

[redacted]

4. Classical Value

The classical McAdams expression for heat-transfer coefficient is:

$$h_g = \frac{K}{d} \; 0.023 \, R_e^{\,0.8} \, Pr^{\,0.4}$$

Consider the data presented in Table 1 for Test D-111-LC-5 at a time of 5 seconds. The heat-transfer coefficient to the graphite in this test, calculated from the McAdams expression, would be

$$R_e^{\,0.8} = (30\,200)^{.8} \qquad = 3830$$

$$Pr^{0.4} = (0.71)^{.4} \qquad = 0.895$$

$$K \qquad = 0.074 \text{ Btu/hr ft } ^{\circ}R$$

$$d \qquad = 0.008 \text{ ft}$$

$$h_g = \frac{0.074 \times 0.023 \times 3830 \times 0.895}{0.008 \times 144 \times 3600 \text{ hr } ^{\circ}R} \qquad = 0.0014 \text{ Btu/in.}^2 \text{ sec } ^{\circ}R$$

The heat-transfer coefficient calculated by the McAdams formula is about twice that calculated from the test data in the subject program. This is qualitatively consistent with Wolf and McCarthy data as presented in ARS Journal 423[2].

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(2) McCarthy, J. R. & H. Wolf, Forced Correction Heat Transfer to Gaseous Hydrogen at High Heat Flux and Pressure in a Smooth, Round, Electrically Heated Tube, ARS Journal, April 1960, p. 423.

[redacted]

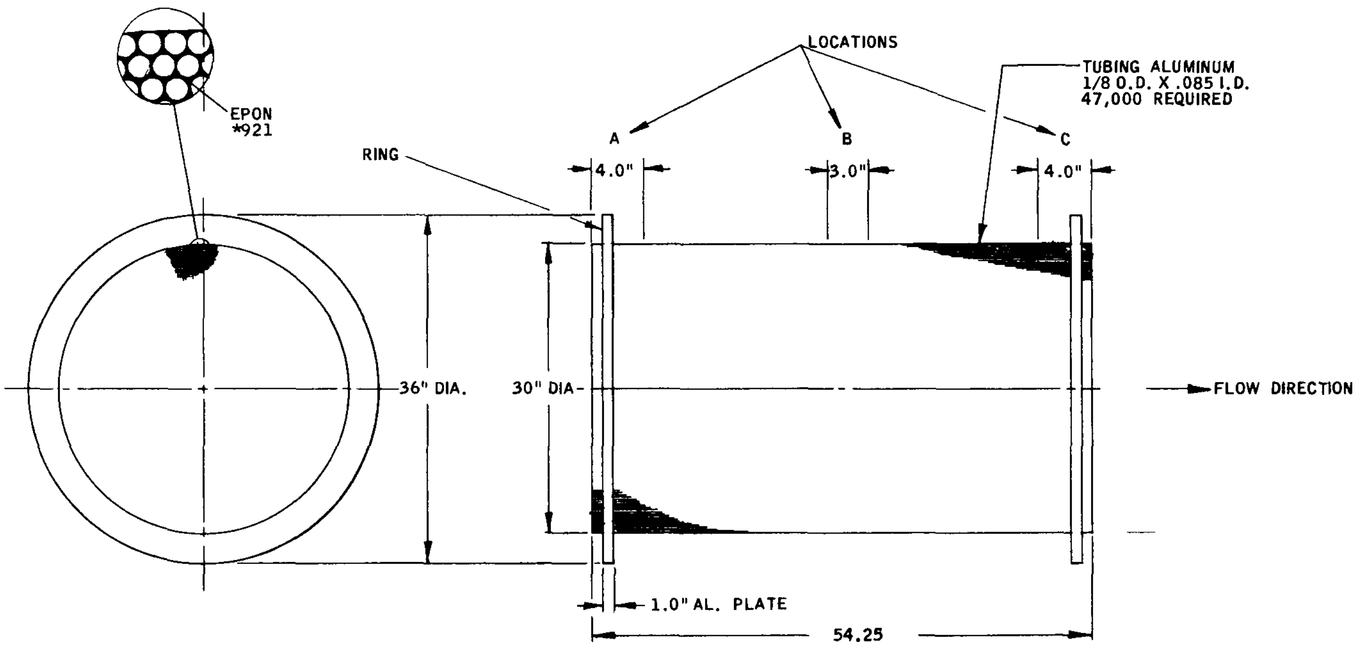
E. SIMULATED CORE DESIGN

Figure 26 illustrates the basic features of an aluminum tube configuration which would provide excellent thermal simulation of the graphite core. It is made up of about 47,000 tubes (0.125-in.-OD x 0.085-in.-ID x 54.25-in.-long) which are grouped in a bundle, the diameter of which is 30 in. The tubes are glued together with Epon 921 resin at both ends and in the center of the bundle. This joining technique was proven in the assembly of the tube bundle for Test D-111-LC-10.

An aluminum ring is attached to the tube bundle (by Epon) at each end for mounting and/or sealing purposes.

The estimated cost to build one such simulated core is:

Material		
Aluminum Tubes	$10,200	
Aluminum Rings	214	
Epon Resin	361	
		$10,775
Labor		
Salary	1,000	
Hourly	12,000	
		13,000
Miscellaneous		1,225
	Total	$25,000



NOTE: AT LOCATION A THE OUTSIDE DIAMETERS OF THE TUBING ARE GLUED TOGETHER - NO LEAKAGE IS PERMITTED BETWEEN THE INDIVIDUAL TUBES OR BETWEEN THE BUNDLE AND THE ALUMINUM RING.

AT LOCATIONS B AND C THE OUTSIDE DIAMETERS ARE PARTIALLY GLUED TO FACILITATE THE ASSEMBLY.

Figure 26

Full Scale-Simulated Core

[redacted]

17

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[redacted]